IMPROVED AEROBIC DIGESTION THROUGH TEMPERATURE AND SOLIDS CONTROL

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Improved Aerobic Digestion Through Temperature and Solids Control

Thesis directed by Associate Professor Edwin R. Bennett

Aerobic digestion of waste activated sludge has been considered as autometabolism of the bacterial cells developed within the activated sludge process. This concept has limited process application since bacteria utilize soluble substrates most efficiently while aerobic digestion is concerned primarily with a destruction and stabilization of solid substrates. It was found that microorganisms other than bacteria could be induced to grow by controlling the sludge environment. These microorganisms, protozoa and rotifers were more efficient in utilizing the solid substrates and thus caused significant process improvements.

Treatment temperatures ranging from 2° to 52°C, sludge solids concentrations ranging from 0.5 to 4.7 percent TVS, dissolved oxygen concentrations ranging from nearly zero to 25 mg/l and both air and pure oxygen aeration were investigated. A series of 54 batch tests and two continuous experiments of 45 to 60 days each were run during the experimental program. Sludge solids, chemical oxygen demand, alkalinity, nitrogen, pH, dissolved oxygen, oxygen uptake, phosphate, settling and stability were closely monitored. The microbiological characterisitcs of the sludge were observed and the microfaunal density measured.

Two temperature optimums were found. One that caused a rapid partial solids destruction and another that resulted in an essentially stabilized sludge suitable for land disposal. The rapid

solids destruction process developed at 42°C ± 4°C. The complete stabilization process developed at 30° ± 4°C. These temperature induced processes were found to be dependent upon the sludges solids concentration in that both were optimized at initial sludge solids concentrations below approximately 2.5 percent TVS. Both processes were time dependent in that the solids destruction process operated most efficiently with a detention time of only three days, and the stabilization process could be operated with only a 12.5 day detention time.

The causative agent for the desirable results obtained at 42°C was the monadidae protozoa. Under batch experimental conditions these protozoa reached their peak population after three days of aeration. This peak population was maintained on a continuous basis with a three day detention time resulting in a high rate partial solids destruction process that operated at an oxygen uptake of 240 mg/hr/gVSS. This process required 2.20 mg of oxygen per mg of VSS destroyed.

The stable sludge produced through aerobic digestion at 30°C was produced by a succession of microorganisms ending with the Bdelloid rotifers. Few of these microorganisms were observed during batch testing; however, they were the predominant microfauna during continuous aerobic digestion. This process, with a 12.5 day detention time, operated at an oxygen uptake of approximately 9 mg/hr/gVSS. It required 1.7 mg of oxygen per mg of VSS destroyed.

The solids destruction process has application in existing wastewater treatment plants that are overloaded with sludge solids.

With a three day detention time, this process can reduce the solids by approximately 50 percent. The sludge stabilization process has wide application since it produces a stabilized sludge highly suited for land disposal with only a 12.5 day detention time. This abstract is approved as to form and content. I recommend its publication.

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INTRODUCTION

General

Wastewater treatment deals with the removal, treatment, and disposal of potential pollutants which are introduced in conjunction with the beneficial use of supply waters. The primary by-product of the removal processes is a semi-liquid waste sludge having a solids concentration of at least 2500 ppm (1). Although this sludge may comprise only 1 to 3 percent of the wastewater flow (2), its treatment and disposal is considered to be the most difficult and costly process in wastewater treatment, accounting for up to 50 percent of the total treatment cost (1, 6, 7). The sludge contains the major portion of the pollutants originally present in the wastewater flow, and as such represents that portion of the flow which must be treated so that final disposal can be made without harmful effects on the environment.

The sludges accumulated in wastewater treatment are broadly classified as raw, chemical, and biological. Raw sludge is that sludge resulting from the initial application of physical solids separation processes to the wastewater flow. It is collected as primary clarifier sediment and is primarily organic in nature. Chemical sludge results from chemical addition to the wastewater flow to enhance solids separation by sedimentation, filtration, or floatation. The characteristics of this sludge depend upon the chemical used, with the sludge generally constituted largely by inorganic precipitates. In addition to the solids entering the treatment plant,

solids are also generated through biological assimilation of the dissolved organic material. These solids comprise the biological sludge, which is predominantly organic in nature. Among the most difficult and expensive of the sludges to treat is the biological sludge produced by the activated sludge process (5, 66). This sludge is particularly difficult to treat because of its relatively high water content, poor dewatering properties, and highly putrescible nature. Current policies in this country requiring secondary treatment will greatly increase the quantities of this waste sludge, and expand the problems and costs associated with its treatment and disposal.

A variety of sludge treatment and disposal processes are documented in the literature (1, 3, 4). The general objectives of these processes are (1) a reduction of the sludge volume by removal of a portion of the liquid fraction, (2) the stabilization or decomposition of the organic fraction, (3) the destruction of pathogens, and (4) the production of a useful by-product (1). These objectives can be generalized into one goal: the economical alteration of the sludge characteristics so that the sludge can be deposited back into the environment in a safe, economical, and beneficial manner. Inherent in this goal is the decomposition or stabilization of the organic fraction of the sludge.

Anaerobic digestion is the process traditionally used for sludge stabilization. It accomplishes a partial oxidation of the organic material with intermediate metabolites such as organic acids, ammonia, methane, and hydrogen sulfide remaining in the sludge (9). Although numerous benefits are cited for this process, its major justi-

fication is that it does decompose the organic matter and render the sludge more acceptable for final disposal (1). The anaerobic digestion process is reasonably well understood, but presents many operating difficulties (1, 7, 10). Waste activated sludge is particularly difficult to stabilize by this process (5).

Aerobic digestion is an alternative biological stabilization process which is receiving renewed attention because of increases in the quantities of waste activated sludge being produced, and recent advances in oxygen diffusor technology. This process has an inherent advantage over anaerobic digestion in that it makes more efficient use of the substrates and, thus, produces a more highly oxidized end product (9). It has been found that aerobic digestion requires less supervision and capital than anaerobic digestion. In recent years it has become particularly attractive for small and modified wastewater treatment plants (8, 10). Aerobic digestion produces a highly nitrified sludge which makes it an ideal pretreatment for land disposal (1, 7, 10, 12, 13).

The costs associated with the various methods of sludge handling vary considerably ($5 to $60 per ton) (1). The costs cited by Dean for the disposal of waste activated sludge (aerobic digestion not included) varied from $15 to $60 with anaerobic digestion followed by land reclamation being the least expensive (8). For land reclamation, Dean provided data showing how disposal costs varied with land costs. Disposal costs increased from $16 per ton to $20 per ton as the land costs increased from $250 per acre to $4,000 per acre. The portion of this cost associated with the anaerobic digester was $12.50 per ton of dry solids.

Cost figures for the aerobic digestion process are not readily available, however, they can be estimated from those for the activated sludge process. For example, using a 2 percent feed sludge, a detention time of 12.5 days, and a capital cost for the activated sludge process of $33.60 per MG, the capital cost for aerobic digestion can be calculated as approximately $14.80 per ton of solids. The power costs associated with aerobic digestion have been given as $.40 per ton of dry solids (5). Thus, the total cost associated with aerobic digestion is calculated to be approximately $15.00 per ton of solids processed. Biological stabilization, either anaerobic or aerobic, followed by land disposal is generally the most economical means of sludge treatment and disposal available.

Study Objectives

Aerobic digestion is a complex biological process influenced by such environmental factors as temperature, solids concentration, oxygen concentration, mixing or turbulence, nutrient concentration, carbon source and concentration, and pH. These factors affect not only the rate of metabolism of a given group of microorganisms, but also the type of microorganisms that develop and accomplish the decomposition. The type of microorganisms providing the decomposition determine the characteristics of both the process itself and the end products. Of the environmental factors listed above, temperature, solids concentration, pH and oxygen concentration are most easily controlled in process application. The objective of the study was to investigate how variations in these parameters influenced the aerobic digestion

process. The parameters were then optimized to:

(1) maximize the rate of solids destruction

(2) obtain a stable end product sludge amenable to land disposal (low in nitrogen) within a reasonable treatment time

(3) obtain an end product from which the solids would separate and compact easily

(4) leave a supernatant which would impose a minimum recycle load on the treatment process.

In addition, since much of the renewed attention in aerobic digestion is concerned with treating high solids concentrations by oxygenation, another objective was to investigate this application of the process to determine the benefits, if any, which might be gained from such a process modification.

CHAPTER II

THEORETICAL ASPECTS

Sludge Microorganisms

General. Activated sludge is a complex mixture of indigenous bacteria, protozoa, fungi and metazoa and other debris. Both the activity and predominance of the microorganisms in the sludge are dependent upon the physical and chemical composition of the influent wastewater and the environmental conditions imposed on the activated sludge process. Changes in either influent composition or operational parameters typically cause a continuous flux in this sludge community.

Aerobic digestion of waste activated sludge is essentially an extention of the activated sludge process. The changes in microbial population induced during aerobic digestion of the waste activated sludge are again dependent upon the environmental conditions imposed. The initial microbial population for the digestion process will be that of the waste activated sludge.

Bacteria. The bacteria found in activated sludge can be broadly classified on the basis of the chemical form of carbon they require as either autotrophic or heterotrophic (9). Autotrophic cells utilize carbon dioxide as their sole source of carbon, while the heterotrophic cells required carbon in the relatively complex carbohydrate forms. Examples of autotrophs found in waste activated sludge are the nitrifying bacteria, Nitrosomonas and Nitrobacter. Typical heterotrophs include species of Achromobacter, Bacillus, Pseudomonas and Micrococcus (18). This bacterial population is the primary removal

mechanism for the dissolved organic matter found in wastewater.

Protozoa. The microfauna found in activated sludge consist primarily of protozoa. Several roles have been proposed for these microorganisms, such as (1) preying on the free bacteria and thereby enhancing clarification and bacterial activity, and (2) utilization of dissolved organics and thereby enhancing chemical purification (18, 19, 20, 21). Of the protozoa, the Mestigophora and Ciliata are of primary importance in activated sludge (26). The following protozoa have been reported as being found in activated sludge: Vorticella aequailata, Vorticella convallaria, Vorticella octava, Epistylis plicatilis, Aspidisca cicada, Euplates bisulcatus, Opercularia minima, and Opercularia phrynganae (19).

Rotifers. Rotifers are the most common metazoa found in activated sludge. Because of their metabolic habits, they are commonly found in wastewaters of low organic content and act as a good indicator of a stable wastewater (18). Ludzack found large numbers of the Bdelloid rotifers in activated sludge having MLVSS of 5000 mg/l and a temperature of 30°C (22). Calloway, based on a number of years of examining metazoa in wastewater treatment processes, reported (23):

> One further item should be noted concerning the metazoa; although they are rarely as numerous in treatment processes as are the ciliates, or as protozoa generally, their smaller numbers do not indicate a lack of importance to the total treatment process. The generally larger consumption per individual metazoa of bacteria and solids, resulting in biochemical oxygen demand reduction, compensates for their smaller numbers.

Calloway, in working with waste stabilization ponds reported that the Bdelloid rotifers were most common at higher temperatures as sludge stability was approached.

These Bdelloid rotifers can both swim free or attach. They are primarily current feeders and draw food particles in with their powerful cilia (24). When a living specimum is viewed, the most conspicious internal organ is the mastax, a muscular organ containing the sclerotized trophi which act as jaws. Food particles which are drawn in are ground by the mastax, digested in the gut and excreted (25). Calloway noted (23):

> ...when the rotifers consume a bacterium, the entire bacterium is not assimilated. Residues of bacterial cell walls as well as some other materials remain. The excreted materials are bundles of particules held together by mucus. This mucus may act in the same manner as the polysaccharide in bonding other bacteria and inert materials to what is the equivalent to an already partially formed floc particule.

The role of the rotifers in the activated sludge process is believed to be similar to that of the ciliates. The feed on bacteria, protozoa and organic debris and thus promote good flocculation and clarification (23). McKinney made the following comment concerning the role of rotifers in the sludge process (18):

> It has only been with the advent of the complete oxidation-type activated sludge systems that the rotifers have been seen as the predominant animal form. The rotifers can utilize larger fragments of activated sludge floc than can the protozoa and survive after all the free-swimming bacteria have been eaten by the protozoa. The rotifers are indicaters of an extremely stable biological system.

The following Bedlloids have been observed in activated sludge: Rotaria rotatoria, Philodina roseola, Philodina erythrophthalama, Adineta vaga and Habrotrocha (23).

Population Dynamics

Competition. Waste activated sludge represents a highly competitive ecosystem in which the predominant organism is determined by its efficiency of food utilization under a given set of environmental conditions. Two types of competition for food can exist, competition for the same food and use of one organism by another for food (prey-predator relationship) (18). In same food competition, the organism which can extract energy most efficiently from the limited environment will survive and predominate. If the substrate form changes, the predomination will most likely change. This phenomenon has been observed in mixed bacterial cultures after the primary bacteria have removed the soluble substrate and a secondary organism develops which feeds on the cellular components released by the first (18).

With a mixed population of both microflora and microfauna, the flora will generally serve as substrate for the fauna. The success of this prey-predator relationship depends upon reaching a balance between the flora substrate, the flora, and the fauna. A mixed population such as this is more efficient in oxidizing the organic waste material. The fauna help maintain a favorable food-microorganism ratio stimulating more active uptake by the flora. The fauna, in utilizing the particulate matter, bacteria, and other bits of organic material, as substrate oxidize another increment of the organic material which would not have been possible with only a bacterial population.

Dynamics. The changes in predominance of the microflora and microfauna during the batch aerobic stabilization of organic matter follow a fairly set pattern as shown in Figure 1. Initially, the flagellates are in competition with the free-swimming ciliates for the bacterial substrate. Generally, the ciliates predominate in this situation since they are more efficient feeders. As stability is approached, the free-swimming ciliates give way to the stalked forms which require less energy for survival. Eventually, the system reaches a point where only the rotifers are able to extract sufficient energy from the environment to survive and thus they prolong and add to completion of the aerobic sludge digestion process.

Stabilization of Liquid Organic Wastes

BOD. Figure 1 shows the changes in microorganism predominance which occur during the batch aerobic stabilization of liquid organic wastes. The amount of oxygen required by these microorganisms to accomplish stabilization is measured by the biological oxygen demand (BOD) test. This test measures the amount of oxygen utilized by the microorganisms in decomposing the organic matter in the wastewater during a five-day period at 20°C. For domestic sewage, this five-day value represents 40-90 percent of the total oxygen required to oxidize the organic matter. In satisfying this total BOD four stages of oxygen uptake can occur, which are caused successively by bacteria, protozoas, rotifers and finally an overall autodestruction. A phenonmena not indicated by Figure 1 which would appear as a new stage in the stabilization process is that of a secondary

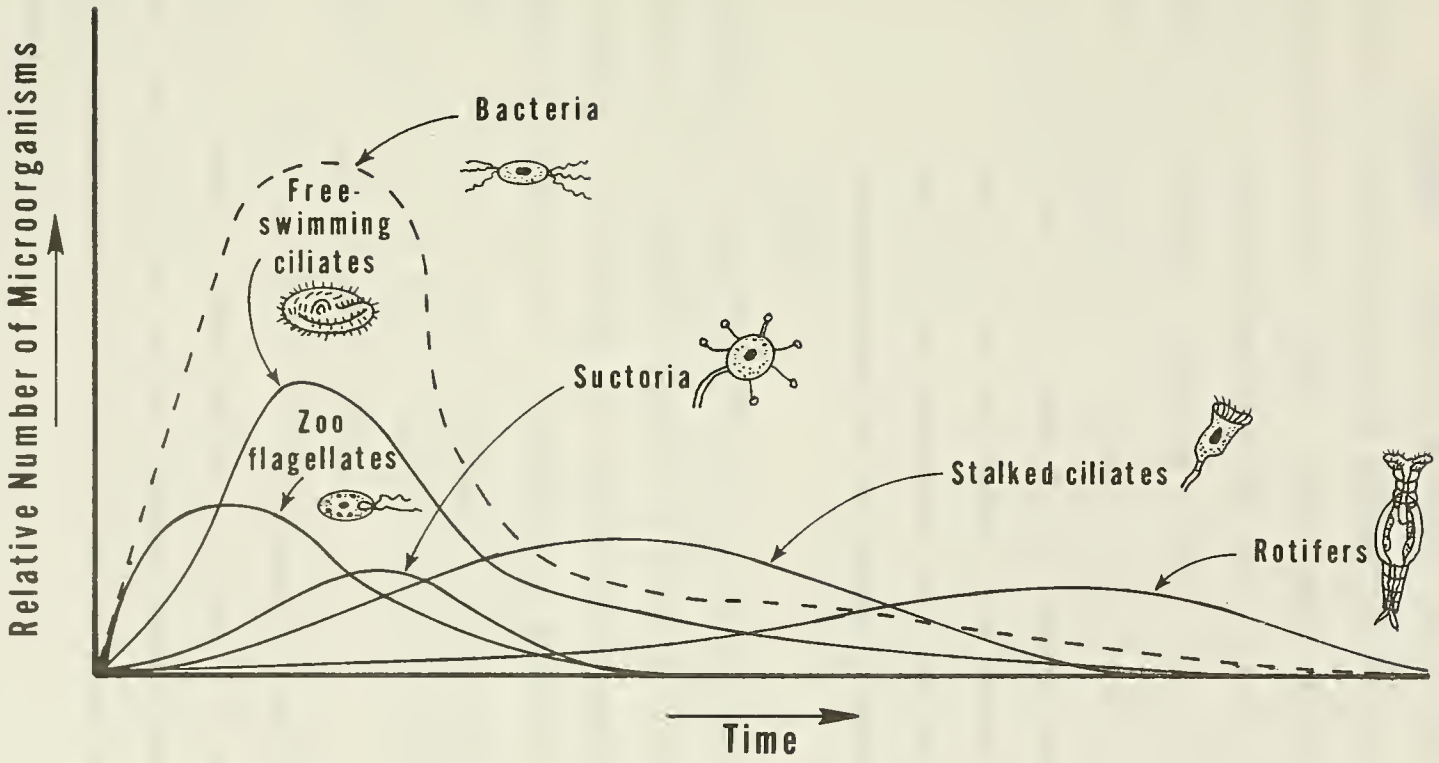

Figure 1

RELATIVE GROWTH OF MICROORGANISMS IN STABILIZATION OF LIQUID ORGANIC WASTES (18).

bacterial growth and predominance caused by a change in the environmental conditions.

Protozoa. Since Butterfield's Work in 1931, a great deal or research has been devoted to determining the role of the protozoa in the stabilization of liquid organic waste materials (18, 27, 28, 29, 30, 31). The protozoa have been implicated as the causitive agent for the "diphasic" exertion of BOD, and as such, contributing some 20 to 30 percent to the overall stabilization (18, 29). It has been concluded that three stages develop during decomposition:

1. assimilation and metabolism by bacteria
2. assimilation andmmetabolism of bacteria by protozoa
3. autodestruction of the remaining bacteria and protozoa biomass

The plateau which appears between the first and second phases was defined as the endogenous respiration phase of the bacterial metabolism, which if no protozoa were present, would persist as a second stage of low magnitude (29). Predation on bacteria by the protozoa, however, increases the long term oxygen uptake of the sludge and causes the so-called second phase of oxygen uptake, thereby decreasing the quantity of sludge remaining (30).

McKinney found in making a complete analysis of the stabilization of a domestic sewage having a 240 mg/l five-day BOD and 1×10^5 bacteria per milliliter initial organism concentration, that the protozoa accounted for 20 percent of the measured five-day BOD (18). He concluded that (18):

> The total oxygen potential of any waste is a fixed value with the only variable being time

> required to exert the demand. If bacteria alone were stabilizing the entire organic mass, the time for complete stabilization would be extended several more days. The metabolism of bacteria by protozoa actually results in a greater demand for energy per unit time and hence oxygen.

Although protozoa are not a significant agent in the activated sludge process itself, which is primarily a bioflocculation and removal process, they have been found to be significant agent in accomplishing the complete stabilization of the organic material.

Autodestruction. After the exogenous substrates have been metabolized, the biomass enters the autodestruction growth stage. It is during this stage that the microorganisms undergo endogenous metabolism, lysis, and regrowth (31). During endogenous metabolism the metabolic processes occur in the absence of exogenous substrates. For the bacterial population it generally begins upon depletion of the soluble substrate and for the protozoa it generally begins upon depletion of the bacterial population. Under starvation conditions, the microbial cell uses various cell components, cell wall, cell membrane and other protoplasmic polymers, in a preferential sequence, to maintain cultural viability. Carbohydrates are used first, then lipids, and finally the proteins and nucleic acids (31). When the microorganism finally dies, it releases the remaining cell biomolecules to the surrounding media.

Autodestruction results in the oxidation of the active cell mass which, based upon a theoretical cell composition of $C_5H_7NO_2$, requires an oxygen uptake of 1.42 mg of oxygen per mg of cells destroyed. McWhorter and Heukelekian confirmed this ratio in finding a 1.4 to 1.0

ratio of oxygen uptake to cells destroyed (30).

Complete autodestruction or oxidation of the biomass by this process does not occur for an activated sludge. A residuum remains which has the characteristics of a polysaccharide and contains significant amounts of fatty acids and organic nitrogen. This residuum, for an activated sludge, has been found to be 20 to 25 percent of the original biological solids produced (30, 32, 33).

McWhorter and Heukelekian found that a constant residual COD and organic nitrogen concentration remained in the supernatant during extended aeration of activated sludge (30). This condition was taken as an indication of either a general absence of cell lysis or the existence of a steady state condition between release and regrowth during autodestruction (30).

Chemical Changes. Aerobic digestion is a biologically mediated decomposition or destruction process. The carbonaceous compounds are oxidized to carbon dioxide and water and the nitrogenous compounds are hydrolized and released as ammonia. Equation 2-1 illustrates the oxidation of the organic matter,

$$C_xH_yO_z + O_2 \rightarrow CO_2 + H_2O \qquad (2\text{-}1)$$

Equation 2-2, the synthesis of cellular material from the organic matter,

$$C_xH_yO_z + NH_4 + O_2 \rightarrow \text{cells} + CO_2 + H_2O \qquad (2\text{-}2)$$

and equation 2-3 the autodestruction of the cell material

$$\text{cells} + O_2 \rightarrow C_O2 + H_2O + NH_4^+ \qquad (2\text{-}3)$$

The nitrogen lost from the cell appears as ammonia in the surrounding media. This ammonia can then serve as a substrate for the Nitrosomonas bacteria and the nitrites produced can serve as substrate for the Nitrobacter bacteria according to equations 2-4 and 2-5 (35).

$$55\ NH_4^+ + 5\ CO_2 + 76\ O_2 \rightarrow C_5H_7NO_2 + 54\ NO_2^- + 52\ H_2O + 109\ H^+ \qquad (2\text{-}4)$$

$$400\ NO_2^- + 5\ CO_2 + NH_4^+ + 195\ O_2 + 2\ H_2O \rightarrow C_5H_7NO_2 + 400\ NO_3^- + H^+ \qquad (2\text{-}5)$$

The hydrogen ions produced during this nitrification process are than neutralized by the bicarbonate ions in the water according to equation 2-6:

$$H^+ + HCO_3^- \rightarrow CO_2 + H_2O \qquad (2\text{-}6)$$

This reaction tends to lower both the pH and alkalinity of the surrounding media. Theoretically, an alkalinity depletion ration of 7:1 (weight of $CaCO_3$: weight of nitrate nitrogen produced) would be predicted: however, a ration of 6:1 has been found in practice (40). Nitrate concentrations in excess of 900 mg/l have been reported for some aerobically digested sludges (17). Figure 2 shows the alkalinity and nitrogen changes that occur duing oxidation of a waste activated sludge (34).

Rate. A wide range of endogenous respiration rates has been reported for the aeration of waste activated sludges. Eckenfelder and O'Connor reported respiration rates of 1.9 to 9.9 mg O_2 per hour per gram of sludge for a domestic waste activated sludge (34). McWhorter and Heukelikian concluded that the endogenous oxygen uptake rate decreased rapidly and approached a minimum value after 10 to 12 days (30). Gates concluded from an extensive literature review that

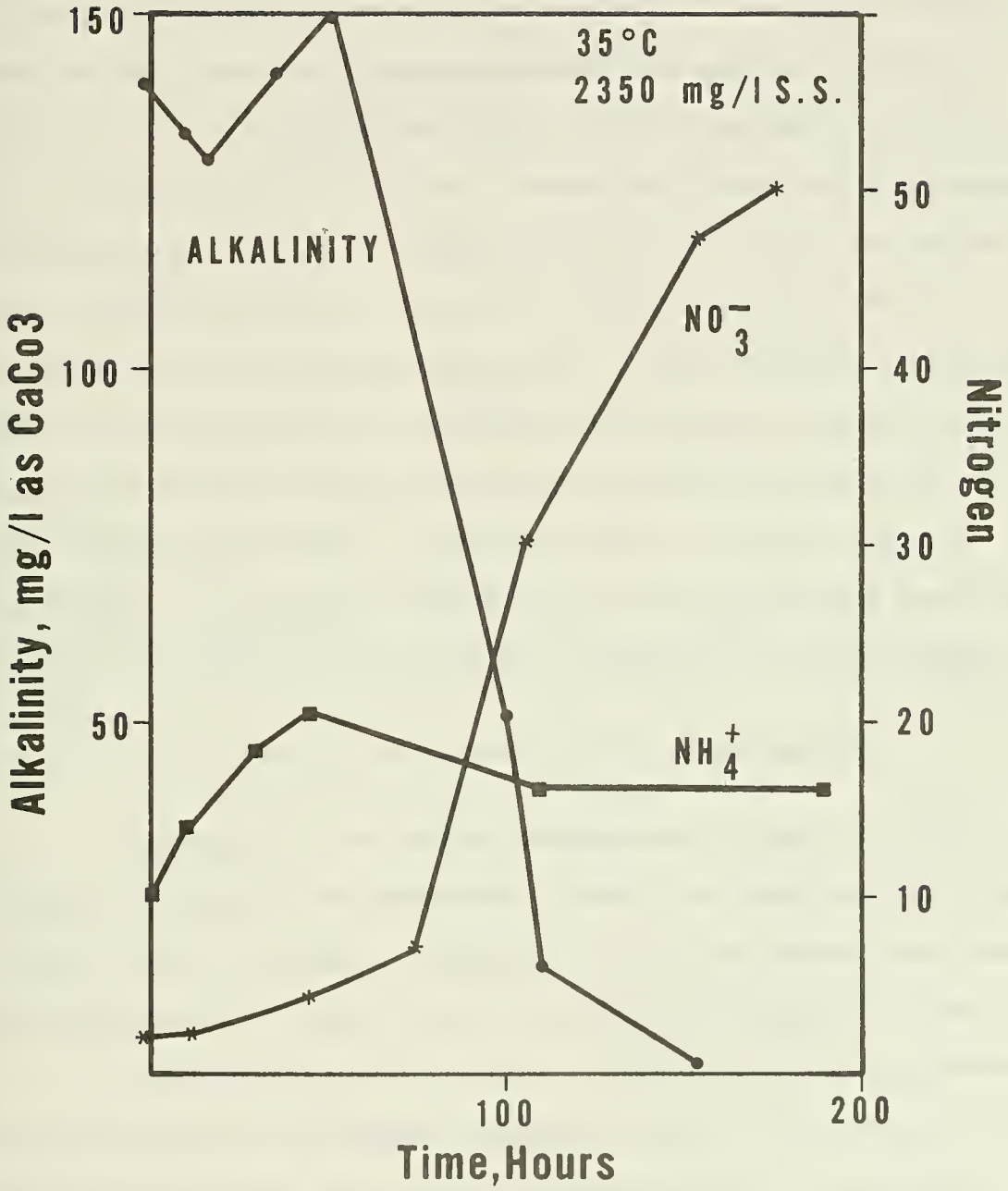

Figure 2

Nitrogen and Alkalinity Changes During Oxidation of Activated Sludge (34)

for various mixed bacterial and yeast cultures there was an initial rapid decline in the oxygen uptake rate per unit weight of dry bacteria followed by a gradual decrease in the respiration rate (31). McKinney reported that the active biomass decomposed at a rate of 0.6 percent per hour (18). Eckenfelder and O'Connor found an oxidation rate of 10 to 12 percent per day at 25°C for a conventional waste activated sludge, a mean oxidation rate of 5.2 percent per day at 21 to 24°C for another waste activated sludge, and a rate of 8 percent per day at 19°C for a step-aeration waste activated sludge (34). These variations in reported rates are most likely due to variations in temperature, substrate used to grow the sludge, microbial content of the sludge, concentration of the sludge and sludge age. In addition, most of the rates reported were based on the volatile solids content of the sludge which generally is not a true indication of the viable fraction of the sludge biomass.

Influence of Sludge Conditions on Microorganisms

Temperature. The optimum temperatures for most activated sludge microorganisms are considerably higher than those normally found in waste activated sludges. Consequently, it can be assumed that these microorganisms never realize their full potential autodigestion rate.

McKinney found that the rate of enzyme reactions approximately doubled for each 10°C increase in temperature up to 35°C consistant with Vant Hoff's law. Above 35°C he found that many of the proteins would undergo denaturation, although some persisted up to temperatures of 65 to 70°C (18). Pfeffer, Leiter, and Worlund summarized the data from McCarty and Cox on the effects of temperature on both anaerobic

and aerobic systems as shown in Tables 2-1 and 2-2 (36). This data indicates process improvement up to 35°C.

TABLE I

EFFECT OF TEMPERATURE ON RATES OF ANAEROBIC DIGESTION (36)

TEMPERATURE	RELATIVE RATE
5°C	0.1
15	0.4
25	0.8
35	1.0

TABLE II

EFFECT OF TEMPERATURE ON METABOLIC RATES IN AEROBIC SYSTEM (36)

TEMPERATURE	RELATIVE RATE
2.5°C	0.02
5.0	0.05
15.0	0.25
25.0	0.5
35.0	1.0

Friedman and Schroeder provided an excellent literature review on the growth and yield of activated sludges (37). Although their review indicated that temperature had little affect on substrate removal rates, it did show that the yield, net mass of organisms grown per mass of substrate utilized, was temperature dependent. Ludzack, et al, reported yield coefficients of 0.53, 0.44 and 0.38 at temperatures of 10°, 20° and 30°C, respectively (22). They concluded that although the activated sludge process efficiency was relatively independent of temperature, the fractional division of purification between oxidative destruction and physical removal varied with a higher rate of catabolism occuring as the temperature increased (22). Friedman and Schroeder concluded from their work that the maximum growth rate and cell yield occurred at 20°C and that a minimum occurred at 41.2°C (32).

Nitrification has also been found to be temperature dependent. Sawyer found the greatest activated sludge growth rate, the lowest nitrifying ability, and the highest sludge nitrogen content at low temperatures (38). Other investigators have found that the optimum rate of metabolism for the nitrifying organisms occurred at approximately 30°C (35, 40, 60).

The temperature at which biological processes are carried out will affect not only the rate of metabolism of a given group of microorganisms, but also the predominant species occurring within a given population. Garber evaluated anaerobic digestion at 85°, 100°, and 120°F and found that a different group of microorganisms predominated at each temperature (84). Ludzack, et al, found that significant

rotifer populations would develop in an activated sludge at 30°C, but were rarely observed at 5°C (22). Cairns found that aquatic microorganisms had definite temperature ranges for optimum growth and that a change in temperature affected the competitive position and relative distribution of most organisms within a given population (39). He found that the protozoa were particularly sensitive to temperature variations and that a given species could survive only within a rather narrow temperature range, although this range could be extended by an encysted or inactive state.

Moisture/Solids Concentration. Another major factor affecting the number, types, and activity of microorganisms found in an ecosystem such as activated sludge, is the moisture content of the material (41, 42). The changes induced by variations in moisture content depend to a large degree upon the nature of the organisms involved. Some microorganisms require a liquid media to feed, some require a liquid media for mobility, and some require solid surfaces for attachment (41). In the extremes, waste activated sludge can be changed from an aquatic environment to a soil environment by thickening, and thus, the microorganisms involved changed from those typifying an aquatic environment to those of a soil environment. It has also been found that the rate of metabolism for the nitrifying microorganisms varies inversely with solids concentration (38).

pH and Alkalinity. Enzymes, and thus, microorganisms, are very sensitive to variations in hydrogen ion concentration. Enzymes and microorganisms have different pH requirements, but with few striking exceptions, optima generally range from about pH 4.5 to

pH 8.5 (44). Most microorganisms cannot survive below a pH of 4.0 or above a pH of 11 (18). Sawyer found that an activated sludge system could produce good purification between pH values of 5 and 11, with the effects produced by pH variations being temperature dependent. Haug and McCarty found in their literature review that the maximum rates of reaction for both Nitrosomonas and Nitrobacter occurred over a pH range from 7 to 9 (35). In addition, they found several reports of nitrification occurring in soils and extended aeration activated sludge plants at pH values as low as 4.5. Since both nitrification and aerobic digestion affect the alkalinity and pH of the system, the initial alkalinity becomes an important parameter in determining whether the pH of the operating system can be maintained within a favorable range.

Dissolved Oxygen and Aeration. The development and activity of aerobic microorganisms is affected by the dissolved oxygen concentration of the system. Most investigators, have found that if a minimum dissolved oxygen concentration is maintained, 0.2 to 1.0 mg/l, oxygen ceases to be a limiting factor in the growth or activity of the sludge microorganisms (18, 34, 46, 47, 48, 49). Kalinske found that this critical dissolved oxygen concentration was a function of floc size and that for a floc size of 100 microns, it was approximately 4 mg/l (57). He concluded that diffusion became the limiting step for these larger floc sizes.

There has been some debate in the literature as to whether a dissolved oxygen concentration above the critical level has any effect on the biological reactions occurring under aerobic conditions.

Zobell found that oxygen tension influenced the metabolic activity of microorganisms in concentrated bacteria and nutrient solutions (50). Poon concluded, from working with a synthetic growth media and bench top activated sludge reactors, that both the substrate removal rate and the endogenous respiration rate were enhanced by using pure oxygen rather than air, even though the dissolved oxygen in the air system never dropped below 5 mg/l (53). His work, however, showed that the reaction was being inhibited not only by the oxygen concentration, but also by the carbon concentration (COD). When he raised the carbon concentration so that this inhibiting effect was removed, the pure oxygen verses air effect became negligible.

Ball and Humenick made an extensive literature review in order to determine what the real advantages were in using pure oxygen in an activated sludge process (54). They concluded that the substrate removal per unit mass of volatile solids in high-purity oxygen systems was not significantly different from that in air systems operating at the same loadings. They further concluded that the biomass developed in high-purity oxygen systems exhibited improved sludge settlability and compaction, but could find no evidence indicating a significant difference in cell yield between air and oxygenated activated sludge systems. Other investigators, in working with pure oxygen in activated sludge, have concluded that the only benefit gained from the pure oxygen was in the elimination of periods of low dissolved oxygen during settling (52).

One point which should be considered in the use of high-purity oxygen is the possible toxic effects of oxygen concentrations

above tolerable limits. Recently is has been found that the cells of higher organisms contain organelles, called peroxisomes, whose major function is thought to be the protection of cells from high oxygen concentration (55). The basic difference between the mitochondrial oxidation reactions and those of peroxisomes is that the oxidation steps in the peroxisomes are not coupled to the synthesis of ATP. The energy released in the peroxisomes is thus lost to the cell. Applied microbiological studies have indicated, however, that dissolved oxygen levels over a range of 0.5 to 30 mg/l do not affect the respiration rate of dispersed cells (57).

Mixing. Below certain levels, which vary with the system under consideration, the degree of mixing applied can effect the transfer of both oxygen and other substrates to the microorganisms. It has been stated that of all the parameters affecting the efficiency of the activated sludge process, few are more important than good mixing (56). Mixing can affect the degree of contact between the microbial cells and the various substrates, and thus, the opportunity for substrate removal. Mixing can effect the transport of substrates to the microorganism through convective diffusion (57). Good gross-mixing and micro-mixing can break the large particles, and thus enhance diffusion to the interior of the floc particles.

Nutrients. Since biological waste treatment processes are dependent on microbial growth, it is necessary that all elements used in the formation of new cells be available. Normal domestic sewage provides a balanced microbial diet with all of the nutrients required for the microbial growth (18).

Sludge Solids Composition and Decomposition

Composition. Activated sludge solids have been found to be made up of 22.2% carbohydrate, 47% protein, 18.7% lipid (as stearic acid) and 7.7 percent RNA, accounting for 95.6 percent of the volatile suspended solids (58). The overall elemental composition has been determined to be 53.1 percent carbon, 8.3 percent hydrogen and 10.7 percent nitrogen accounting for 72.1 percent of the suspended solids (58). Membranes, the most difficult of the cell components to degrade biologically, make up a large percentage of the total dry mass of eucaryotic cells and have been found to be 40 percent lipid and 60 percent protein (8).

Decomposition. The changes which organic materials undergo as they are biologically converted to less complex compounds are termed decomposition or stabilization (18, 42, 44). Decomposition is essentially a mineralization process resulting from the utilization of the bound chemical energy found in organic molecules. The carbohydrates are broken down into smaller polysaccharides, simple sugars, carbon dioxide, and water. The lipids are hydrolyzed to organic acids and then converted to carbon dioxide and water. The proteins are hydrolyzed to amino acids, deaminized and taken to ammonia, carbon dioxide, and water. The nucleic acids are hydrolyzed, releasing soluble phosphate and soluble nitrogen into solution (58, 59). These nucleic acids are approximately 10 percent phosphorous as P (58). The actual steps involved in the decomposition and the resulting intermediate metabolites vary greatly depending upon the nature of the organic material, the microbial population, and the environmental conditions (42, 50).

Aerobic versus Anaerobic Decomposition. Biooxidation in the presence of sufficient free oxygen to satisfy the demands of the microorganisms is termed aerobic decomposition. Aerobic organisms obtain most of their energy through respiration, the transfer of electrons from organic fuel molecules to molecular oxygen (9). The non-nitrogenous compounds such as starches, sugars, lignin, cellulose, organic acids, and oils are decomposed (lignin and cellulose very slowly) and coverted into a succession of simpler compounds leading eventually to carbon dioxide, water, phosphates, and sulfates. The mineral constituents of the original materials remain, primarily as salts of calcium, phosphate, magnesium sulfate, potassium carbonate and sodium chloride (42).

Biooxidation in the absence of free available oxygen is classified as anaerobic metabolism. In anaerobic decomposition the microorganisms utilize final electron acceptors other than free molecular oxygen. When this final electron acceptor is an organic substance, the process is called fermentation (44). The rate of anaerobic decomposition is slower and generally less complete than aerobic decomposition (42). Much of the nitrogen, carbon, hydrogen and oxygen of the original material is converted into complex intermediates such as the organic acids, acetic, butyric, and propionic (34). In anaerobic digestion, another group of microorganisms, the methane producers, often become active. The most important of these bacteria are those the degrade acetic and propionic acid to methane (41). The methane formers have a very slow growth rate and are usually considered the rate limiting step in the anaerobic digestion process

(3). Stabilization under these conditions comes with the evolution of methane and carbon dioxide.

In the areas of catabolism and anabolism, the anaerobic way of life represents the primodial condition (9). The evolution of aerobic cells provided a more efficient means for converting organic substrates into molecules of much lower energy content than could be achieved by anaerobic processes. Most aerobic cells still utilize an anaerobic process, glycolysis, as the first step in extracting energy from substrate molecules. Through further oxidative reactions they then take the products of glycolysis to carbon dioxide and water.

Ammonification. Ammonification may be defined as the formation of ammonium ions by the sludge microorganisms during decomposition of the nitrogenous compounds (42). The primary source of ammonia in the degradation of waste activated sludges is the proteinaceous material. Before proteins enter the catabolic pathways of the microorganism, they undergo complete deamination, i.e. removal of the amino groups. The carbon skeleton which remains then undergoes normal oxidation (9). Most organisms tend to reuse ammonia derived from the catabolism of amino acid; however, some is ultimately excreted (9).

Nitrification. The terminal form of nitrogen resulting from aerobic decomposition is the highly oxidized nitrate form. Nitrification, the biological conversion of ammonia to nitrates, adds to completion of the overall oxidative decomposition process. It is carried out by the nitrifying bacteria which utilize ammonia as an energy source and carbon dioxide as a carbon source (35). These organisms, in the course of oxidizing the ammonia, produce additional organic carbon and nitrogen which can also enter the decomposition process. The

net result of nitrification is a more completely oxidized end product.

Denitrification. The nitrates formed through nitrification provide a means for biologically lowering the nitrogen content of the sludge through biological denitrification. True biological denitrification, or nonassimilative removal of nitrogen, is performed only on the oxidized forms of nitrogen. Thus, the oxidation of ammonia, nitrification, is essential for nitrogen removal by this means. Biological denitrification is an anaerobic process with the nitrate ion acting as the final electron acceptor (3). In this process nitrates are reduced to nitrogen gas and carbon compounds are oxidized. Most of the denitrifying organisms are facultative and are commonly found in wastewater (60). The denitrification reaction has been represented as (60):

$$4\ NO_3^- + 4\ H^+ + 5\ CH_2O \rightarrow 2\ N_2 + 7\ H_2O + 5\ CO_2$$

Humification. It has been found that the organic matter found in wastewaters and waste activated sludges is not susceptible to total oxidation. A relatively stable residuum remains, which for waste activated sludges has been found to be 20 to 25 percent of the original biological solids produced (30, 32, 33, 61). McWhorter and Heukelekian found this inert organic residue to be 12 percent of the initial COD, while Washington and Hertling reported it as 10 percent of the COD removed (30, 62). This end product has been described as a humus-like, biologically stable material (1).

The decomposition of organic material in sludges is very similar to the decomposition of organic materials in soils. Total oxidation or decay is not achieved and a residual material, humus, remains. Humus has been described as (42):

> Humus denotes soil organic material which has undergone extensive decomposition. It is not a homogenous compound; it has no definite composition. It is a dark heterogenous mass consisting of the residues of plant and animal materials. Lignin makes up 40 to 45 percent and protein 30 to 35 percent of the total humus. The remainder is composed largely of fats, waxes and other residual materials.

Research on humus has shown that the soil fauna are the decisive agent in the decomposition and humification process (59).

> Coprogenous and noncoprogenous humus micromorphologically is nearly always easy to distinguish. The knowledge of dropping forms in general allows one to recognize the role of particular animal groups in the decomposition of organism residues. In the coprogenous part of the humus better decomposition and humification dominates by far. Valuable humus forms are inconceivable without the particular participation of the soil fauna in their genesis. The soil fauna is also entirely responsible for the mixing and combining of the organic substance with inorganic parts of the soil.

Stability. The objective of both aerobic and anaerobic decomposition in the wastewater treatment field is the production of a stable end product sludge; that is, a sludge which contains insufficient energy to support anaerobic decomposition with its accompanying nuisance conditions. There is no agreed, quantified point, however, which defines this desirable end product (63). General terms such as "odorless" and "good drainability" have been applied. In anaerobic digestion, the degree of stabilization has been related to methane production and to the percentage reduction of the volatile solids (64, 56). Jann, et al, selected pH as a simple, rapid, and accurate method of determining the completion of composting (66). They defined stability as that compost condition that would no longer undergo anaerobic fermentation. For aerobic digestion such variables as the volatile matter content in

the sludge, intensity of respiration, or reductive activity have been suggested as indices for the degree of stability (63). Okazaki and Kato, in discussing Hehrs article, suggested the release of soluble orthophosphate as an index (63). In practice, the only positive way of determining whether product sludge has reached the desired degree of stability is to submit it to a test under conditions similar to those which will be encountered in the subsequent sludge treatment steps.

CHAPTER III

PREVIOUS AEROBIC DIGESTION STUDIES

General

The literature has many reports dealing with the general performance of the aerobic digestion process, although, most of these reports provide very little information concerning the conditions under which digestion was performed. Temperature, solids concentration, and dissolved oxygen were usually not controlled. The reports usually provide information on only the rate and extent of the volatile solids destruction. Initial oxidation rates of 5 to 12 percent per day and total volatile solids reductions of 30 to 55 percent after 5 to 15 days are common at approximately 20°C are common (1, 5, 34, 67, 68).

Drier described the settling characteristics of aerobically digested sludge as "poor" when digestion was carried out for less than 30 days (15). He also reported that the pH of the sludge dropped with prolonged aeration. Lawton and Norman, in addition to encountering nitrate concentrations as high as 900 mg/l, also found that the pH dropped to levels which could inhibit the process (pH of 4.5) (69). They investigated the possibility of artificially controlling the pH but found that this method of process control resulted in a significant decrease in the volatile solids reduction.

Aerobic digestion has been found to produce a dark brown stable sludge that readily gives up water when placed on a sand drying bed (10, 16, 74, 76). When allowed to settle, the resulting supernatant was found to be low in nutrients, solids, and COD (15, 72). Aerobic digestion, when compared directly with anaerobic digestion, was found

to provide a more completely oxidized end product (69).

Temperature

Of the environmental parameters which affect aerobic digestion, temperature can produce the most significant process variations. Even though the relationships between temperature and the rate and extent of the reaction have been studied, little is known regarding the relationship of temperature to the microbial population or the stability of the end product sludge. In addition, little is known of the dependence existing between temperature and the other two major environmental parameters, solids concentrations and dissolved oxygen.

Experiments conducted by Drier with a mixture of raw primary and waste activated sludge at temperatures of 15°, 20°, and 35°C showed the following temperature phenomenon (1):

(a) at a detention time of 60 days, temperature had no effect since digestion was complete at all temperatures.

(b) a minor temperature effect was noticed at a very short detention period of five days.

(c) 10 and 30 day detention periods were noticeably influenced by temperature.

(d) higher temperatures produced greater volatile solids reductions.

A comparative study of mesophilic (35°C) and thermophilic (52°C) aerobic digestion made by Loehr indicated that (17):

(a) thermophilic oxidation was more efficient in reducing ether solubles.

(b) Thermophilic oxidation produced a sludge which would not settle well.

(c) mesophilic oxidation produced a sludge which settled readily, produced a clear supernatant and was granular when dried (17).

Lawton and Norman reported on a three-year aerobic digestion study in which the effects of detention time, temperature, pH, aeration rate, and loading rate were investigated (69). They obtained eight-day volatile solids reductions of 28, 34, and 38 percent at temperatures of 15°, 20° and 35°C, respectively, and concluded that temperature had a highly significant effect on the volatile solids reduction rate. Reyes obtained 20-day volatile solids reductions of 30 and 67 percent at 8° and 60°C respectively, while Carpenter and Blosser obtained an approximate doubling of the volatile solids reduction rates in going from 20° to 30°C (70, 73). Barnhart found that temperatures below 20°C were significantly retardant to the aerobic digestion process (74).

From these studies it can be concluded that temperatures up to 35°C, and possibly as high as 60°C, produce significant increases in both the rate and extent of the aerobic reaction. In addition, there seems to be evidence that indicates that the 20°C to 35°C temperature range produces approximately the same results, while temperatures below 20°C significantly hinder the process.

Solids Concentration/Loading

The volatile solids destruction rate has been found to vary inversely with the solids concentration and solids loading. Drier, in an investigation previously described, found that volatile solids removal varied inversely with loading (15). Lawton and Norman found that increased detention times produced a highly significant increase in volatile solids reduction as the digester loading rate was increased

up to 0.1 lb VS/day/ft^3 (69). Malina, in making a comparative study between aerobic and anaerobic digestion of a primary sludge, found an optimum loading rate of 0.17 lb VS/day/ft^3 for the aerobic digestion process (63).

Wuhrmann and Leidner reported on extensive tests carried out at the Jona Wastewater Treatment Plant between July 1969 and April 1971 (75). They could find no relationship between the chemical composition of the waste activated sludge and the characteristic changes expected during stabilization. A good correlation, however, was found between the degree of stabilization obtained and the solids concentration. Solids concentration, oxygen input, mixing, and the speed with which oxygen was distributed to all points in the stabilization tank were found to be decisive factors for effective stabilization. With an oxygen concentration of approximately 3 mg/l, a temperature of 17.5°C, a solids concentration of less than 20,000 mg/l, and a detention time of 6.3 days, they obtained a sludge which remained "fresh" during subsequent thickening and dewatering (75).

Reynolds reported on both bench scale and pilot scale waste activated aerobic sludge digestion studies (2). A summary of the results from his bench scale tests at five different concentrations is shown in Table 3. There was a decrease of oxygen uptake, a decrease in the decay constant, and an increase in the time required for stabilization as the solids concentration increased. Reynolds stated that, "Since sludge age gets greater as the suspended solids increase it follows that the degradation rate constant, K, would also decrease as the solids increased." It is difficult for the writer to see how the sludge ages could have been different in a batch experiment

TABLE III

EFFECTS OF SOLIDS CONCENTRATIONS

ON AEROBIC DIGESTION*

CONCENTRATION mg/l	TIME 0 UNIT O_2 mg/hr/gVS	Kd Day-1	STABILIZATION TIME DAYS	STABILIZER UNIT O_2 mg/hr/gVS
8,400	25.2	0.72	4.00	4
12,400	20.2	0.62	4.75	3
15,050	19.5	0.51	6.00	3.2
21,260	15.0	0.44	8.88	2.3
22,700	8.6	0.34	9.88	1.5

* From Reynolds (2)

run for the same length of time with the same sample of sludge. Rather, it seems as if his data shows an inverse relationship between the initial solids concentration and the reaction rate constant.

Jaworski, et al reported that solids concentration was an important variable (71). Batch aeration of sludges which had total solids concentrations of 0.75 and 3.06 percent for six days at 20°C gave COD reductions of 50 and 12 percent respectively. They did not, however, come to any conclusion regarding the effects of solids concentration.

Dissolved Oxygen/Pure Oxygen Aeration

Cohen recently reported on the use of pure oxygen in aerobic digestion studies conducted at the Metropolitan Denver Sewage Disposal Plant (11). Batch tests were conducted using a 4.5 percent suspended solids, float thickened, waste activated sludge. A ten-day test conducted at 20° $\pm$5°C produced a 40.7 percent VSS reduction in eight days and a 61.3 percent VSS reduction in ten days. It was concluded from another investigation using high purity oxygen for aerobic digestion that a non-objectionable, stabilized sludge could be obtained with a 7 to 9 day detention time and a 20 to 30 percent reduction in volatile suspended solids (77). In addition, it was found that the stabilized sludge resulting from this process was more difficult to dewater than the oxygenated waste activated sludge that was used as the feed sludge. These tests were run on sludges with initial volatile suspended solids concentrations ranging from 1.5 to 4.4 percent. Processing temperatures were not given.

The use of pure oxygen in the above studies has allowed the aerobic digestion process to be applied at solids concentrations above those which could be handled with air aeration. It is safe to conclude that air could not have maintained aerobic conditions throughout the sludge mass at these high solids levels. The above investigators, however, failed to conduct comparative aerobic digestion studies with various combinations of temperature, solids concentration, and dissolved oxygen (either provided by air or pure oxygen) to determine where the process might be optimized. It can be concluded from their work that high solids concentration can be aerobically digested with the use of pure oxygen aeration.

Design Criteria

Loehr has presented an approach for the design of an aerobic digestion system for waste activated sludge (17). In general, he estimated the total and active mass of the sludge to be treated and applied a first order decay equation to determine the solids retention time required. Next he applied the ratio of 1.4 grams of oxygen per gram of volatile solids destroyed to determine the oxygen requirements. He found that successful loading rates ranged from 0.10 to 0.14 lb VS/ ft^3/day.

Drier presented the following design criteria (15, 1):

(a) Solids loading for primary plus waste activated sludge of 0.20 pounds S.S. per capita per day of 3 to 4 percent solids.

(b) Air flow of 15 to 20 cfm per 1000 cubic feet of digester capacity and a dissolved oxygen concentration of 1 to 2 mg/1. 1.42 grams of oxygen per gram of sludge volatile solids.

(c) Power requirement of 10 BHP per 10,000 population equivalent.

(d) Detention time, for waste activated sludge alone after thickening, of 10 to 15 days. More time is required if the temperature is less than 60°F.

(e) Tank designs are normally not covered or heated. The tanks may be designed for spiral roll or cross roll aeration. The system should allow for sludge thickening and supernatant decanting.

The aerobic digestion system used by Reynolds was constructed according to the following criteria:

(a) Plant capacity - 2 MGD

(b) Population served - 20,000

(c) Waste activated sludge flow to be 0.85 percent of plant flow or 15,500 gal/day.

(d) Solid concentration of waste activated sludge flow to be 9,000 mg/1.

(e) Digester size - 15 x 30 x 68 feet
Digester volume - 31,100 ft^3

(f) Detenton time to be 15 days based on flow for waste activated sludge.

(g) Volume to be 1.55 ft^3/capita

(h) Air flow to be 20 cfm per 1000 cubic feet volume.

These various criteria can be generalized as follows:

(a) Detention time of 10 to 15 days at temperatures above 20°C and dissolved oxygen concentrations above 2.0 mg/1.

(b) Loading of 0.10 to 0.20 pounds of volatile solids per day per cubic foot.

(c) Air flow rate of 15 to 20 cfm per 1000 cubic feet of digester to supply 1.4 grams of oxygen per gram of volatile solids destroyed.

Performance

Aerobic digestion has not been widely applied to date and few operating reports are available. The results, when available, are often presented in qualitative rather than quantitative terms. The aerobic digesters at the OSO plant in Corpus Christi, Texas, produced, with a ten-day detention time, a stable sludge which could be placed on the treatment plant lawns without creating a noticeable odor (1). Batavia, Illinois, noted cost savings in their overall sludge handling system after instituting aerobic digestion of a mixture of primary and waste activated sewage sludge (17, 1).

Plant application studies were conducted at the Metropolitan Denver Sewage Disposal Plant for the purpose of minimizing the amount of waste activated sludge to be processed by the vacuum filters and incinerators (15). Under operational conditions it was possible to convert sufficient activated sludge aeration basins to aerobic digesters to provide an eight-day detention time. Studies conducted for four months indicated that 26.5 percent of the total waste activated sludge solids could be destroyed prior to concentration, vacuum filtration and incineration. The power costs for providing an adequate supply of air amounted to approximately $0.35 per million gallons of waste treated or $1.33 per ton of sludge destroyed by aerobic digestion. An additional benefit found was that the aerobically digested sludge solids would settle to approximately twice the concentration of the waste activated sludge.

Kehr reported on the operation of the aerobic digester used at the Nordhorn, Germany Wastewater Treatment Plant (63). The major

portion of the wastewater treated by this plant was from textile industries which is reflected in the very low volatile content of the waste. The digester had a volume of 700 cubic meters and provided a detention time of 4.65 days. The feed sludge was 6 percent solids, 50 percent being volatile. The digester was fed at the rate of 6.4 Kg volatile solids per cubic meter per day (0.4 lb per cubic foot per day). Neither the quality of the end product nor the organic destruction obtained was discussed. A detention time of 8 to 10 days for "common" domestic sewage and a tank volume of 0.01 cubic meters per capita (approximately 30 percent of the volume of a comparable anaerobic digester) were recommended (63).

Reynolds reported on the operation of a small aerobic digestion system which was designed to treat 15,500 gallons per day (2). Studies were conducted at three operating solids levels, with an average hydraulic detention time of 10.4 days. The solids levels were controlled by recycling the thickened aerobic digested sludge. The waste activated sludge fed to the digester averaged 10,730 mg/l, 72.3 percent of which was volatile. The volatile solids in the digested sludge averaged 53.6 percent. A volatile solids reduction of 56.4 percent was obtained with an average oxygen uptake of 1.82 pounds per pound of solids destroyed. The oxygen uptake rates were essentially constant for all operating solids levels.

Ahlbert and Boris evaluated the aerobic digestion process at seven treatment plants in the Province of Ontario (10). The conclusions reached are as follows:

1. The design of aerobic digesters should be based on solids retention time rather than hydraulic retention time.

2. Volatile solids reduction does not provide a reliable indication of sludge stability. The specific oxygen uptake rate is one of the best indicators of sludge stability.

3. Aerobic digestion can produce a stable sludge.

4. Aerobic digestion produces a supernatant low in nutrients and organic material which represent an insignificant load if recycled.

5. An air flow rate of 20 cfm per 1000 cubic feet of digester capacity resulted in solids deposition and oxygen deficiencies.

CHAPTER IV

EXPERIMENTAL PROCEDURES

Introduction

Since decomposition of waste activated sludge by aerobic digestion is a biochemical process, any factor that affects the activities of the sludge organisms will necessarily affect the rate of decay of the organic material. The many factors affecting the rate of decomposition can be placed into two general groups: (1) nature of feed sludge (including sludge age, microorganisms, and chemical composition), and (2) sludge conditions within the digester (including solids concentration, aeration, temperature, mixing, dissolved oxygen concentration, alkalinity, and chemical composition).

Sludge age affects both the rate and extent of the decomposition process. In general, aerobic digestion will be most rapid and complete with young sludges. This is largely due to the higher level of stored substrates within the microorganisms. While no attempt was made to control the initial sludge age in this investigation, the experimental apparatus allowed for six individual experiments to be run with the same sludge sample and, thus, eliminated this parameter within the experimental set.

Of the many factors within the digester which can influence the rate and extent of decomposition, those chosen for investigation in this analysis were temperature, solids concentration, alkalinity/pH and types of microorganisms. These variables were chosen on the basis of their potential for defining the process and suggesting possible

directions to be taken in making process improvements.

Sludge Collection and Start-Up

The sludge collection procedures varied slightly from run to run depending upon the experiments to be conducted. The sludge utilized was return activated sludge obtained from the Metropolitan Denver Sewage Disposal District Plant. The sludge, as obtained from the treatment plant, had a concentration of 5,000 to 10,000 mg/l and a theoretical sludge age of three to seven days. When a sludge concentration of greater than 1.5 to 2 percent was required, the sludge was treated with Dow C31 polymer and allowed to settle for approximately one hour in 30 gallon plastic containers. The supernatant was then decanted and the sludge placed on a fine screen for further concentrating. When both low and high concentrations were required in the same experimental run, the low concentrations were obtained by diluting the screened sludge with deionized water. In runs requiring concentrations of only 2 percent, the sludge was merely treated with polymer and gravity thickened. Likewise, for solids concentrations of 1 percent, the solids were merely settled and the supernatant decanted. Preliminary experiments indicated that these various collection and concentration procedures did not significantly effect the experiment results.

The experiments were started by bringing the sludge sample to the temperature and dissolved oxygen levels as quickly as possible. In the initial temperature study, the sludge was brought to temperature prior to introduction into the reactors. In the subsequent experiments the sludge was brought to temperature within the reactor by increasing

the output of the external heating devices. The contents of the reactors were mixed and aerated for 30 minutes before the zero time sample was drawn.

Apparatus

The experimental apparatus was designed to provide positive temperature, dissolved oxygen, and aeration control. Six bench scale reactors were constructed using six-inch diameter plastic pipe. The basic unit consisted of a five-foot section of six-inch ID plastic pipe. The reactor, when filled with twenty liters of sludge, had a freeboard of approximately one foot for foaming control. Four port holes were provided for observation of the physical conditions within the reactor. Level indicators were installed for reactor volume measurement and evaporation loss makeup. These basic units were built and mounted in sets of three as shown in Figure 3.

Mechanical mixing was provided by 1/25 H.P. Cole Parmer variable speed motors. A 5/16-inch diameter stainless steel shaft with two three-inch diameter impellers provided the mixing. A 5/16-inch plastic bearing served both to steady the shaft and as the point of entry for the aerating gas. The two impellers were positioned at one and eighteen inches above the bearing, respectively. These impellers, when operated at 625 RPM, created a high level of turbulence which kept the solids in suspension with a minimum swirl and vortex.

As previously mentioned, either oxygen or air could be introduced through the shaft bearing beneath the bottom impeller. The gas flow control panel, shown in Figure 4, was equipped with rotometers and control valves for gas flow measurements, and flow regulation. This

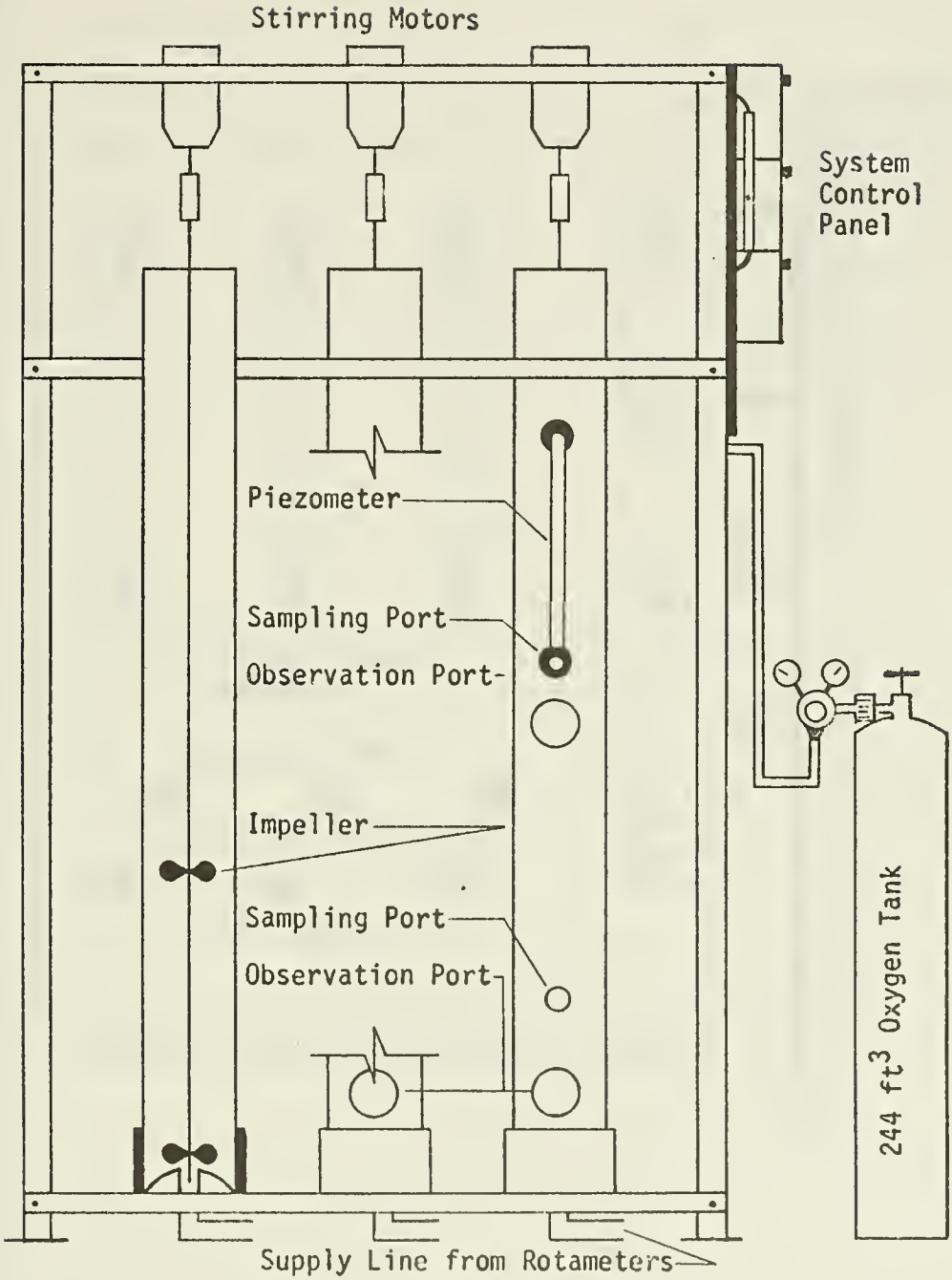

Figure 3

Diagram of Bench-Scale Apparatus
Used in Laboratory Research

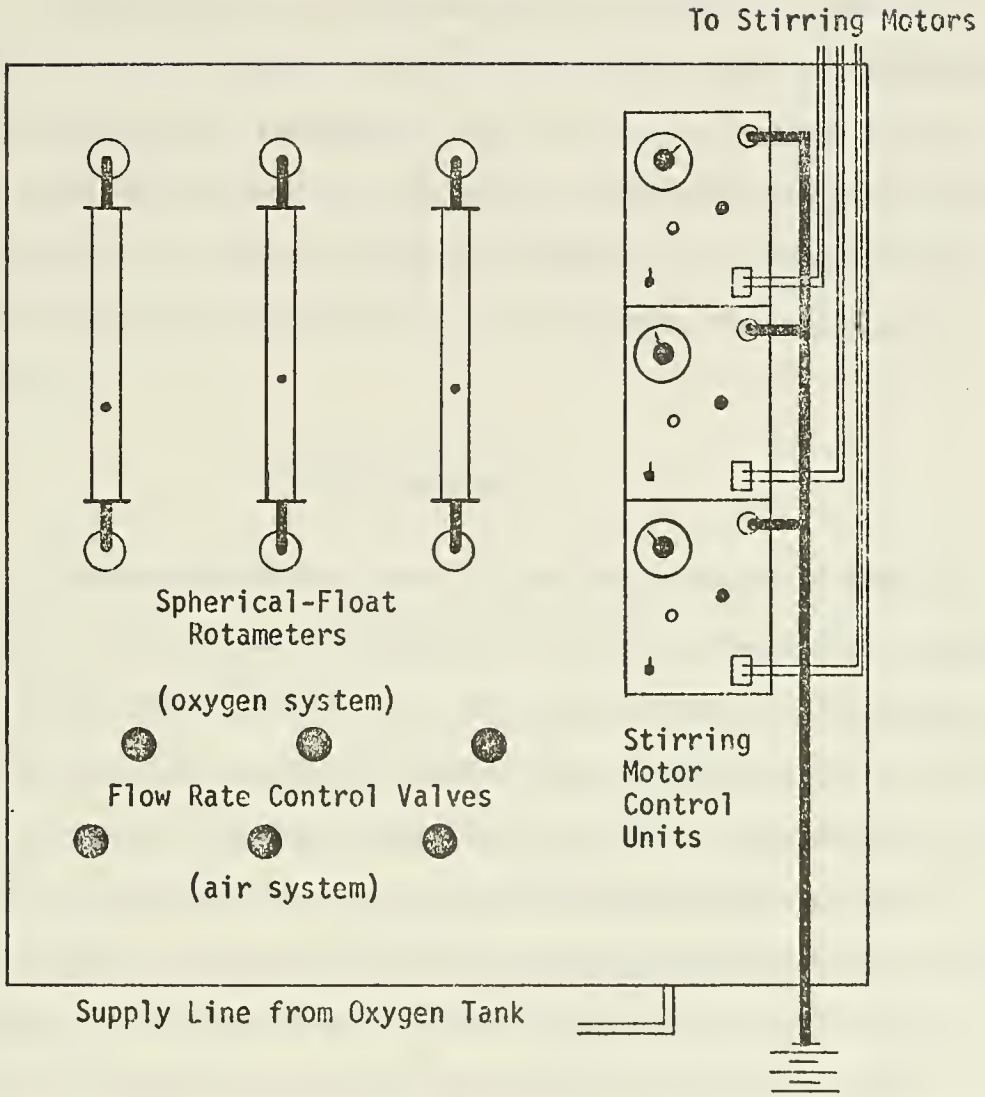

Figure 4

Diagram of System Control Panel

control system had the capability of providing either pure oxygen, air, or any desired combination of the two.

Temperature control was achieved by two means. One set of three reactors was placed in a temperature control room for maintenance of the desired reactor temperature level. The other set was run with heating tapes wrapped around the individual reactors. The temperatures were controlled by a voltage regulator attached to the heating tapes. These units provided the capability of maintaining the temperatures within $\pm 2°C$.

Warburg Analysis

Warburg studies were made to gain preliminary information regarding the effects which variations in solids concentration, temperature, and pure oxygen could have on the aerobic stabilization process. An 18-place American Instrument Company Warburg apparatus and a 7-place Precision Scientific Warburg apparatus were used in these studies. The first set of experiments was run for 185 hours using return waste activated sludge from Metropolitan Denver Sewage Disposal District Plant. The variables investigated were solids concentration (2,000, 4,000, 9,000 and 14,000 mg/l) and oxygen concentration of the gas phase. The experiments were conducted at 20°C using 5 ml samples and a shaker rate of 100 oscillations per minute.

A second set of batch experiments was conducted with the Warburg using return activated, primary, and floatation concentrated waste activated sludges from the Metropolitan Denver Sewage Disposal District Plant. The variables investigated in these experiments were

oxygen concentration in the gas phase, solids type and concentration, and temperature. Experiments were conducted for 70 hours at 20°C and 30°C using 10 ml samples of the float sludge (3.5% TVS), a mixture of primary and waste activated, (4.4% TVS), waste activated (2.4% TVS), and waste activated (3.0% TVS). The waste activated sample was centrifuged to 3% TVS and then diluted back for the 2.4% TVS sample. The mixed sample was made by mixing the primary and waste activated samples in the ratio of three to one.

Reactor Operation

Operation of the reactors under batch conditions consisted of making up the evaporation loss, drawing samples, and maintaining the reactor logs. The oxygen or air flow, dissolved oxygen concentration, pH, motor speed, settling rate, sample volume, and evaporation loss makeup volume were recorded on these logs. The frequency of making the recordings and their associated control corrections varied throughout the duration of the experiment. Readings were made on some parameters such as dissolved oxygen concentration and temperature as often as practical during start up to assure that the experimental design conditions were reached and maintained. Operation of the aerobic digesters was generally quite simple and trouble free. The only problem encountered was one of occasional excessive foaming during certain phases of the decomposition process. The problem was generally corrected by reducing the gas flow rate.

Operation of the reactors under continuous flow conditions consisted of monitoring pH, temperature, dissolved oxygen concentration,

respiration rate, settling rate, and sludge community. The reactors in the first continuous run (Appendix L) were fed fresh sludge twice a day for the entire experiment, while those in the second run (Appendix M) were fed twice a day for the last five weeks of the experiment. Feeding was accomplished twice a day be first removing one half of the daily flow and then adding an equal volume of fresh sludge which had previously been brought to the temperature of the reactor. The reactors in the first continuous run were fed fresh sludge each day while in the second, the six reactors were fed in series, each with a 2 1/2 day detention time. The evaporation loss was made up daily after feeding. Two ten liter gas mixed reactors were operated during each of the runs as reference points (reactors 7 and 8). Close monitoring of both the feed sludge and the reactor effluent was performed to provide historical data which was used to determine when the reactor had reached a steady state condition. After samples were drawn for analysis, the daily flow (feed sludge addition) was reduced to maintain a constant detention time at the reduced reactor volume.

Sampling and Analysis

In accordance with predetermined schedules, 250 ml samples were drawn and preserved with two ml of a 40 mg/l HgCl solution. The samples were then stored at 3°C until all analyses had been run. The maximum storage time (three days) occurred during Runs 1-4 when the early sampling was quite heavy. The maximum storage time for Runs 5-9 was 24 hours. The alkalinity tests in Runs 5-9 were run on fresh, unpreserved samples. The effects of preservation and storage on the COD and alkalinity tests were periodically checked and found to be within

the normal variance of the test results.

Suspended Solids. The basic method followed in obtaining data indicative of the suspended solids concentrations (total, volatile and fixed) was that suggested by Harada, et al (78). This method was followed except for the modifications discussed below. Coarse fiber asbestos was used, which reduced the required washing time. A mat approximately 1/4-inch thick was built up on the glass fiber filter, rather than the 1/16 to 1/8-inch mat recommended, so that a sample volume of 20 ml could be filtered within 15 to 20 minutes filtration time. All firing was done at 550°C for 30 minutes. Drying was accomplished in a mechanical convection oven.

Total Solids. The total volatile and fixed solids were determined in accordance with Standard Methods (79) with the exception that 50 ml samples were used and fired for 30 minutes.

Chemical Oxygen Demand. The chemical oxygen demand was determined as recommended in Standard Methods (79). The samples were diluted so that the test could be run with 10 ml of a .25 normal potassium dichromate solution.

Alkalinity. The alkalinity of the samples was determined by titrating a 50 ml sample to the potentiometric end point of 3.7 with a Beckman pH meter (79).

Nitrogen. All forms of nitrogen were determined in accordance with Standard Methods (79). Distillation followed by back titration of the boric acid solution was used for the ammonia determination. A 10 ml sample was used for both the ammonia and organic nitrogen determinations. The nitrate nitrogen concentration was determined by the Brucine Method

using a dilution factor of 1250. The nitrite concentration was determined by the method recommended for "high nitrite samples" using a 25 ml sample.

pH. The pH was determined with a Beckman pH probe (79).

Dissolved Oxygen. The dissolved oxygen was determined by the membrane electrode method using a P/S Galvanic Cell Oxygen Analyzer (79). Determinations could be made using a BOD bottle for solids concentrations up to three percent. Higher solids concentrations required that the sample be placed in a 125 ml Erlenmyer flask so that adequate mixing could be developed.

Respiration Rate. Respiration rates were determined with the same basic apparatus as that described above for the dissolved oxygen test. The probe was left in the sample and the stirring continued while readings of the dissolved oxygen were recorded as a function of time on a Heath Servo Recorder Model 5M-20A. This test provided a relative indication of the rate at which the organisms would take up oxygen under the specified test conditions.

Phosphate. Phosphate concentrations in both the supernatant and mixed liquor were determined by the Stannous Chloride, Solvent Extraction method (79).

Protozoa and Rotifer Density. Estimates of fauna density were obtained from microscopic examinations of sludge samples. A known sample volume, 0.065 ml, was placed on a slide. A plastic cover plate, 48.35 mm^2 was then placed over the sample. This provided a sample thickness of 0.135 cm. A calibrated Whipple ocular micrometer was used for counting within a known field of vision, $1.15 \times 10^{-2} cm^3$.

Three random counts were made, averaged, and multiplied by the scale factor of 8.7×10^4 to give the estimated organisms per liter. The Whipple micrometer was also used to estimate the size of the organisms to aid in general identification. Spot checks were made with a standard blood cell counting chamber to verify the results obtained with the Whipple micrometer.

Microscopic Examination. Microscopic examinations of the sludge were made on both the samples prepared for the fauna density determination and fixed slides. The fixed slides were prepared and stained with Huckers crystal violet.

Settling. Settling analyses were made to determine both the relative rate at which the solids would settle and the general characteristics of the solids and supernatant after settling. This test was run by placing 1000 ml of the sample in a 1500 ml beaker. The interface height and general solids and supernatant quality were recorded after 30 and 60 minutes.

Stability. An evaluation of the relative stability of the sludge was made by incubating a sample of the material without aeration in an air-tight BOD bottle at a temperature of 37°C. The time required for septic conditions to develop, as indicated by a black color and hydrogen sulfide odor, was recorded and taken as a relative indication of the sludge stability.

CHAPTER V

RESULTS AND DISCUSSION

Introduction

A laboratory study was made of the aerobic digestion process using a conventional secondary waste activated sludge. Included were Warburg studies, batch bench scale studies, and continuous bench scale studies of the aerobic digestion process. Warburg studies were undertaken to develop preliminary digester design information. This phase of the work was followed by a series of 54 batch experiments, as shown in Appendix A, which were run in sets of four to six, using the laboratory digester previously described. Temperature, solids concentration, dissolved oxygen, method of aeration (air or oxygen) and detention time were varied and the effects on the microbial populations and overall process performance evaluated. The process information gained from the batch studies was applied on a continuous feed basis to a set of six reactors with various detention times and then to a set of six reactors each with a two and one half day detention time, all being fed in series giving a total detention time of fifteen days. Each set of values shown on the figure in the following discussion from a single sludge sample.

Solids Degradation

Temperature. As expected, temperature significantly influenced the rate of destruction of the organic matter. Percent reduction of volatile suspended solids is shown in Figure 5 as a

function of treatment time for a single sludge sample processed on a batch basis at temperatures ranging from 2° to 42°C. The variation produced by temperature is most pronounced after six days of treatment. Comparing two reactors it can be seen that raising the temperature from 2°C to 13°C increased the average 15 day digestion rate, by a factor of 2. The incremental temperature increase from 13°C to 24°C increased this rate by an additional factor of 1.33. The COD and the VSS were still being destroyed at a significant rate for both the 42°C and 31°C processes after approximately ten days of treatment. It will be shown later, that this time period is a sensitive stage in the stabilization process.

The temperature range was next expanded to included 50°C. From this work it was found that 50°C actually had a detrimental effect on the process in that it produced a lower organic reduction. This is shown in Figure 6. The figure also shows that a treatment temperature of 29°C resulted in the highest rate of COD destruction.

Typical results obtained from the batch aerobic digestion of a one percent VSS sludge using treatment temperatures of 31°C and 41°C are shown in Figures 7 and 8. The reductions shown in Figure 7 were essentially equal for the two temperatures and indicated that the two processes were similar. Comparing oxygen uptake rates as shown in Figure 8, however, indicated very different process characteristics. A very dramatic change in oxygen uptake occurred for the 42°C process between two and five days of aeration. This phenomenon was observed during all batch experiments at 42°C except those run above 2.1 percent volatile solids. This peak in the oxygen uptake rate

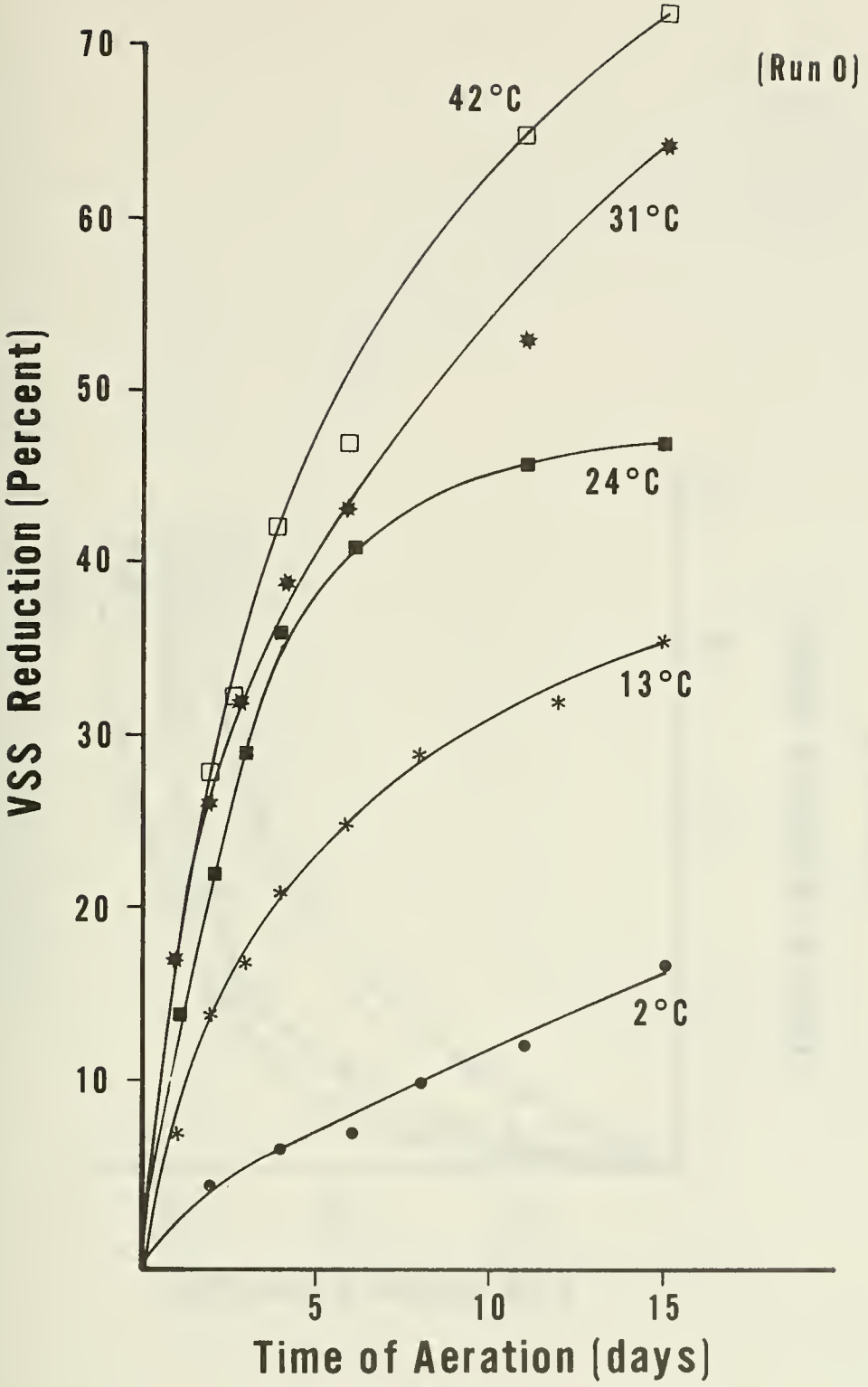

Figure 5

Temperature Effects on Aerobic Digestion

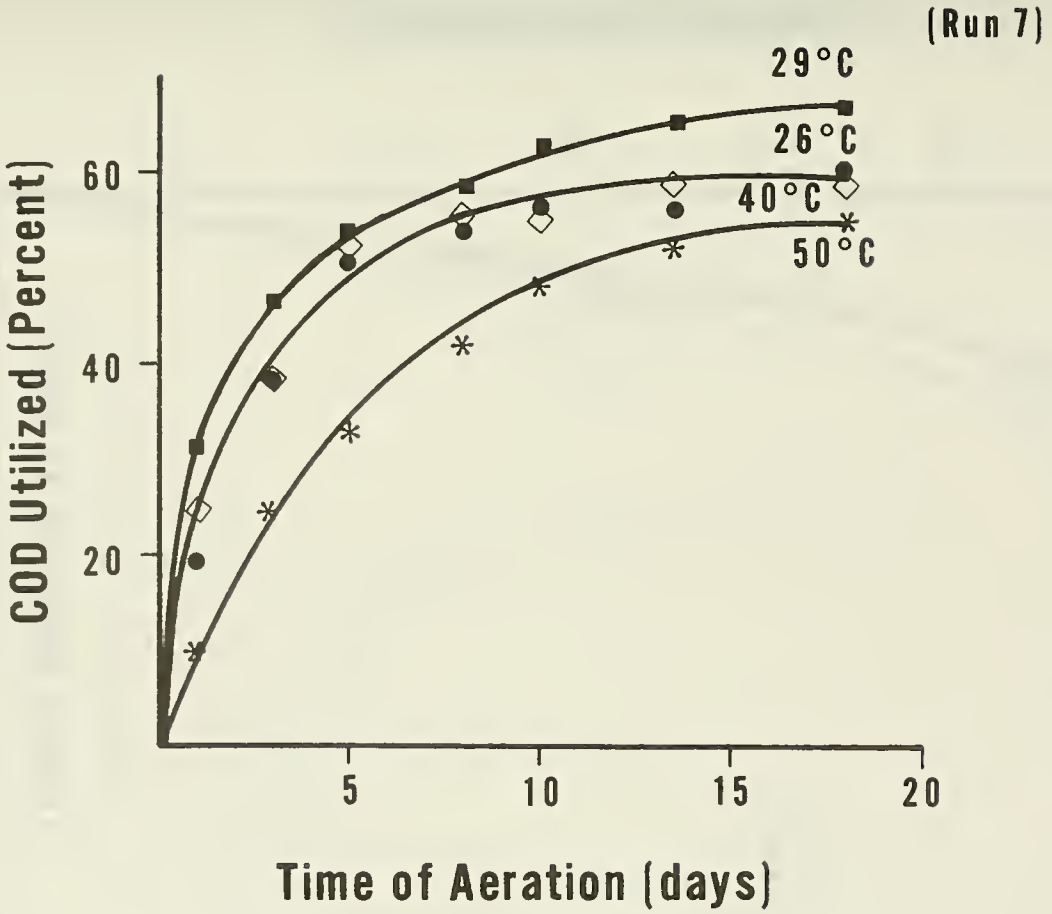

Figure 6

Temperature Effects on Aerobic Digestion

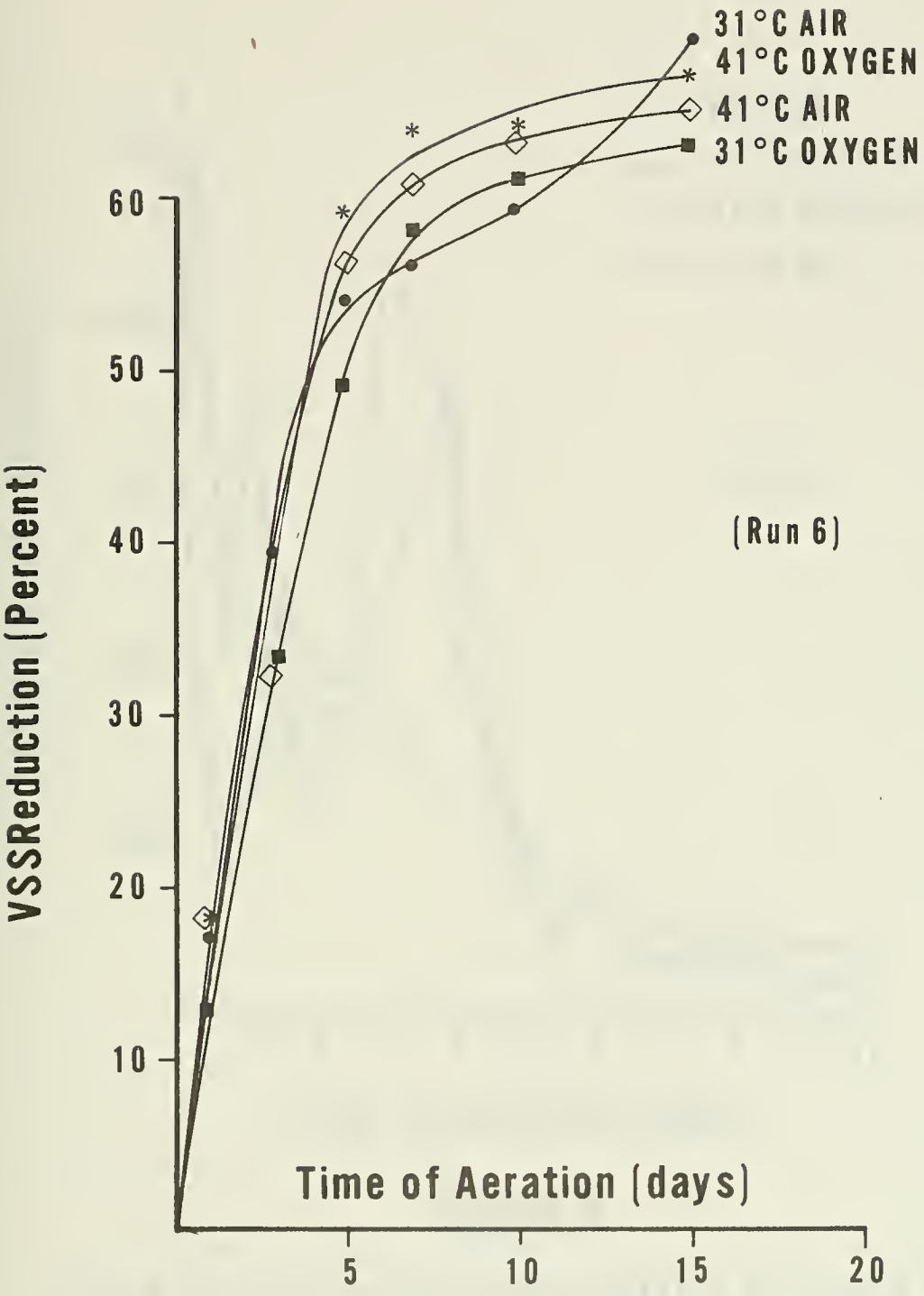

Figure 7

Batch Aerobic Digestion at 31°C and 41°C

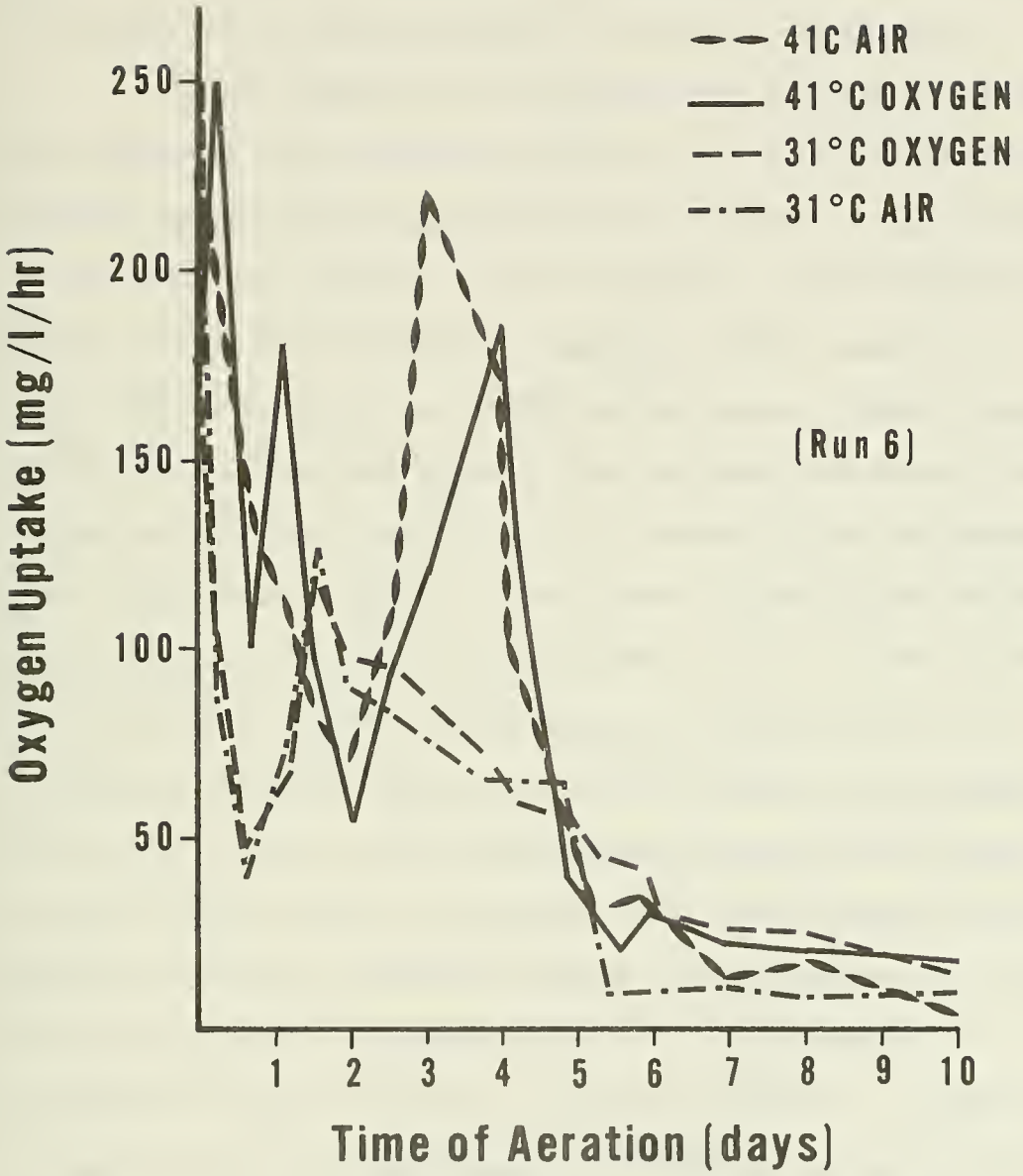

Figure 8

Batch Aerobic Digestion Oxygen Uptake at 31°C and 41°C

always corresponded to an observed peak in the protozoa population. The high oxygen uptake rate and protozoa population persisted for only a relatively short period of time under batch conditions and thus, were not readily observable in the COD or VSS results.

Aerobic digestion at temperatures of 30°C and 42°C under the continuous feed conditions confirmed that these two temperatures produced optimum operating conditions for the aerobic digestion process. It was found that digestion at 42°C resulted in a very high initial rate of solids destruction while digestion at 30°C resulted in a very complete but lower rate stabilization process. Aerobic digestion at 42°C with a three day detention time produced a 48 percent VSS reduction. The same reduction at 30°C required a five day detention time. This shown in Figure 9. Also shown in this figure are the VSS destructions at 30°C using detention times of 5, 6, 10 and 15 days and the results obtained from processing for three days at 42°C followed by treatment for ten days at 30°C (total 13 day detention time). This 13 day, 30°/42°C combination process did not perform as well as the ten day, 30°C process. Thus, even though the early stages of the aerobic digestion process were enhanced at 42°C it was found that raising the temperature to 42°C was detrimental to subsequent biological activity at reduced temperatures. Operation at temperatures above approximately 31°C severly limited the diversity of the microbial population and thus hindered the stabilization process.

The VSS destruction and the oxygen uptake rate achieved using the six reactors in series, each with a two and one half day detention time, are shown in Figures 10 and 11. As previously

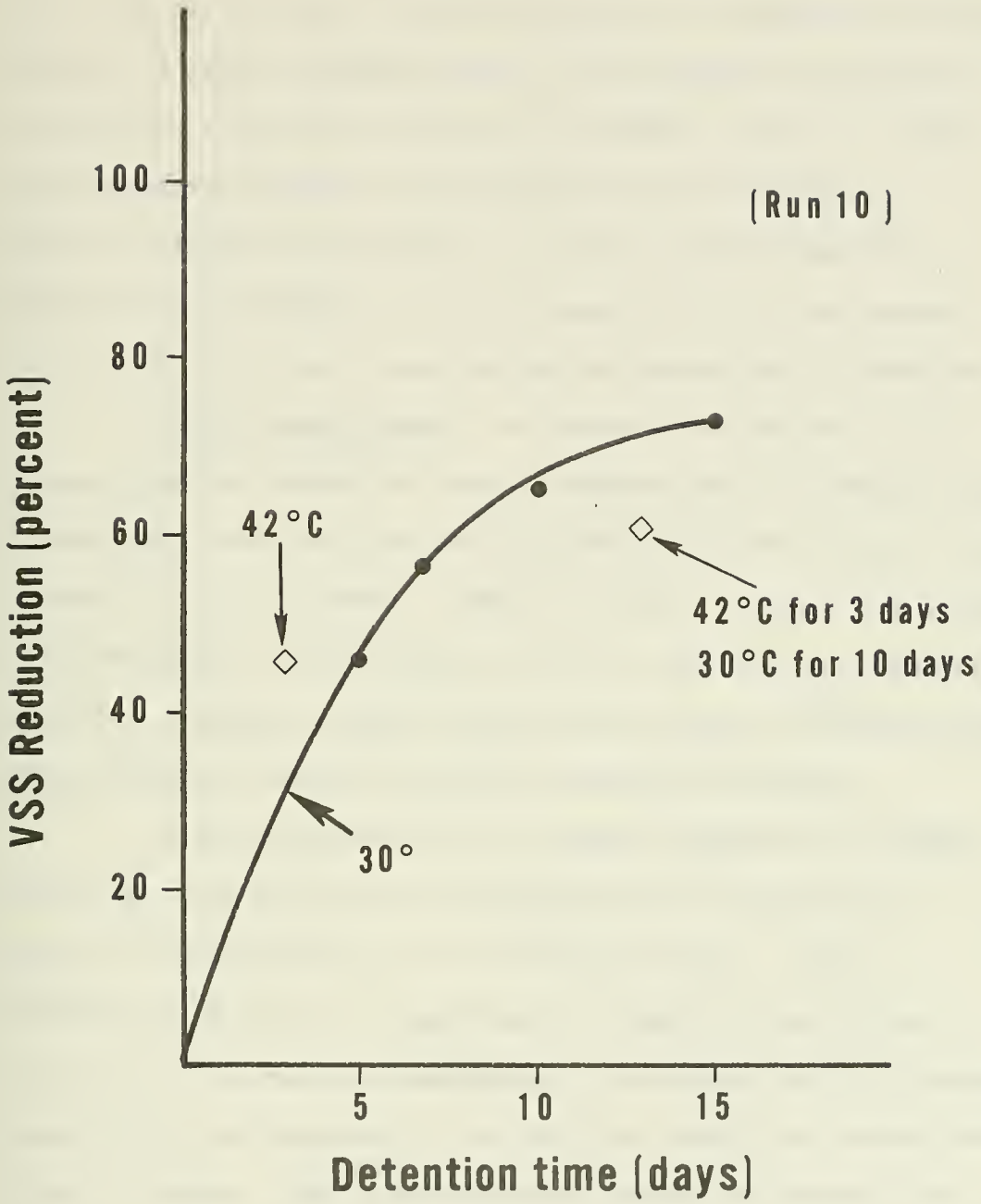

Figure 9

Continuous Aerobic Digestion at 30°C

mentioned, these reactors were fed in series so that a total detention time of 15 days resulted. Aerobic digestion was essentially complete within 12.5 days of treatment under these operating conditions as indicated by the slope of the curves in Figures 10 and 11. These curves approach asymptotes after approximately 12.5 days of aeration indicating the presence of a very stable sludge. The stability test indicated that this sludge could be stored without aeration for more than a month without developing septic conditions.

Solids Concentration. The economic feasibility of the aerobic digestion process is highly dependent upon the maximum solids concentration that can effectively be treated and the detention time required for this treatment. These two factors dictated that tankage requirements, and, thus, the major portion of the capital investment required. Treatment at high solids levels and short detention times should constitute the most economical operating conditions.

It was found that both the sludge temperature and solids content affected the type of microorganisms that developed and thus, the characteristics of the resulting process. Aerobic digestion was found to be significantly retarded at high solids levels for all processing temperatures. Here again, as with elevated temperatures, the diversity of the microbial population became significantly limited. The limited microbial population affected the reaction and the characteristics of the resulting end product. Both the rate and extent of the VSS destruction were impaired. The resulting sludge was relatively unstable and it was more difficult to settle.

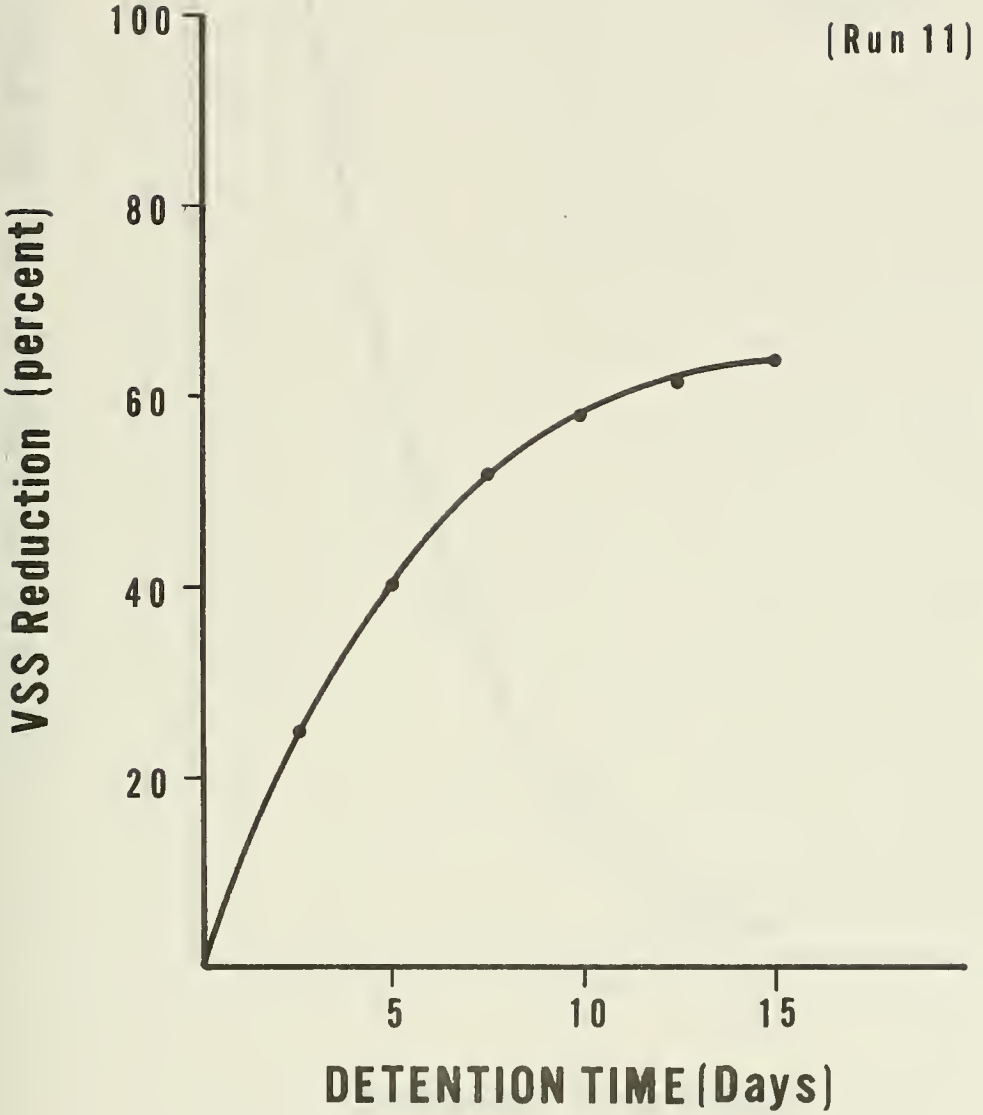

Figure 10

Continuous Aerobic Digestion at 30°C

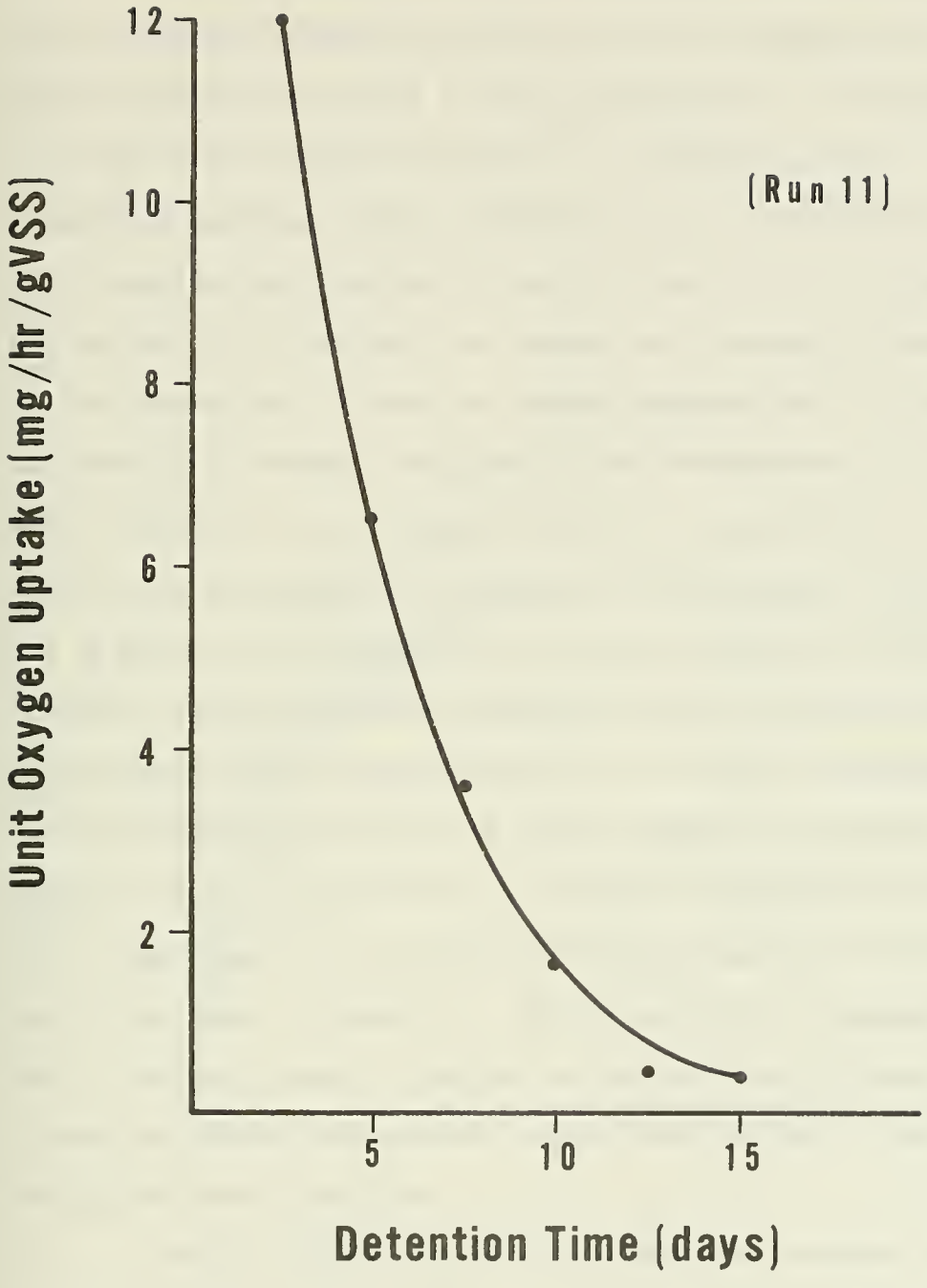

Figure 11

Aerobic Digestor Oxygen Uptake as a Function of Detention Time at 30°C

Initial testing was done to determine the maximum solids level that could be mixed and aerated with the laboratory scale aerobic digester units used in this investigation. It was found that a solids level of 47,000 mg/l could not be mixed or aerated. A measurable dissolved oxygen concentration was not achieved until this sludge had been aerated for nearly 44 hours. At a reduced solids level of 37,000 mg/l, the sludge could be mixed and aerated. At this solids level a dissolved oxygen concentration of 10 mg/l was maintained throughout the reactor when aerated with pure oxygen. Aerobic digestion of this sludge produced a total volatile solids reduction of approximately 28 percent at a temperature of 26°C and 38 percent at a temperature of 52°C with eight days of batch treatment. These low solids destruction rates indicated that the process was inhibited even though a D.O. of 10 mg/l was maintained. Further analysis showed that the aerobic digestion process was inhibited at 2.2 percent TVS at a processing temperature of 25°C and at approximately 2.5 percent TVS when processing at both 30° and 42°C as shown in Figure 12. The VSS destruction obtained with the 2.2 percent sludge is similiar to that obtained by digesting at a dissolved oxygen concentration of less than 1.0 mg/l. Both processes were significantly retarded.

Both the oxygen uptake and the observed microbial populations provided further insight into the effect that high solids concentrations had on the process. At 42°C and solids concentrations less than 2.5 percent TVS, a peak in the oxygen uptake curve occurred between the second and third days of batch aerobic digestion as shown in Figure 8.

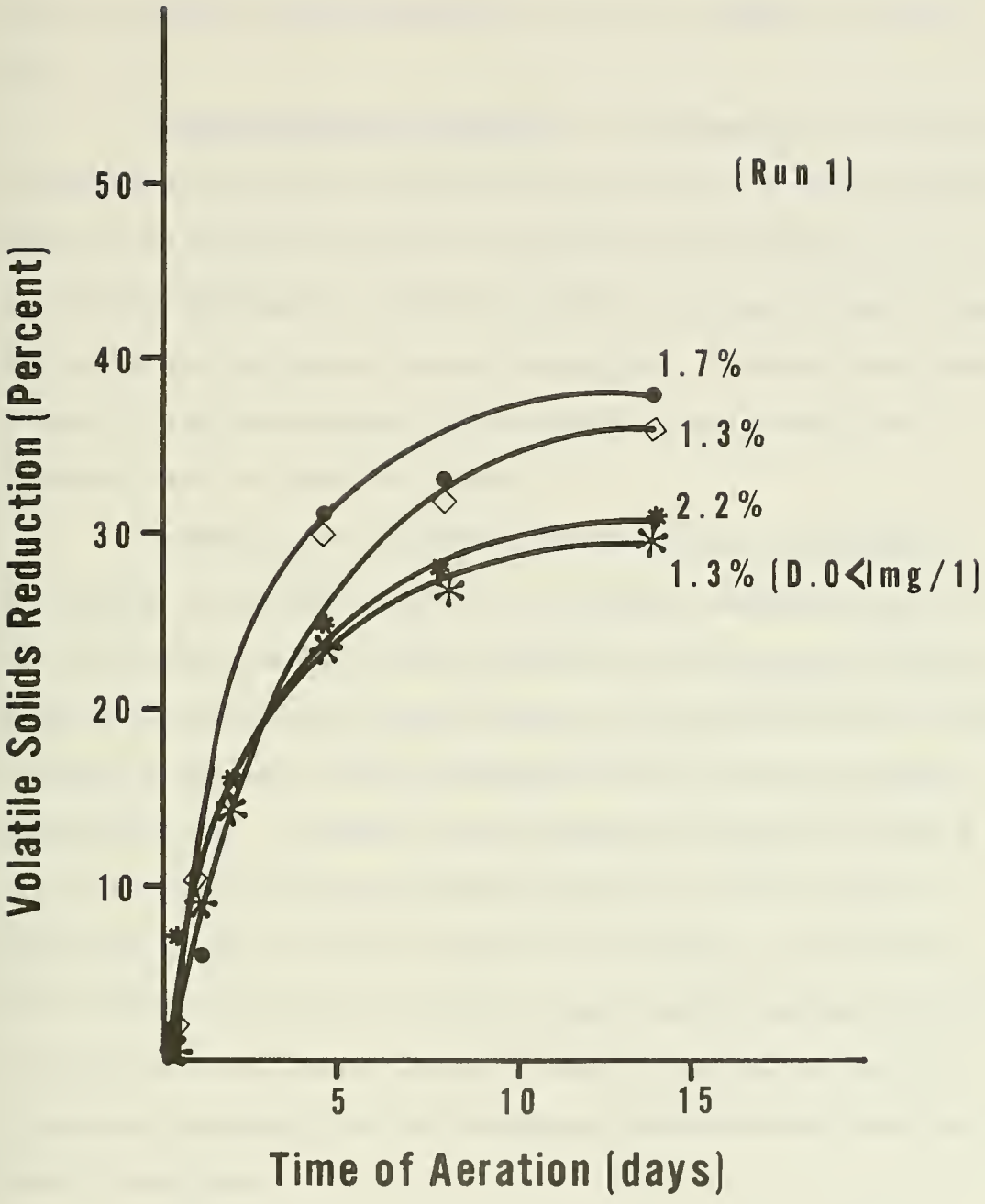

Figure 12

Solids Effects on Batch Aerobic Digestion at 25°C

In addition, a dramatic growth of protozoa was observed during this same time period. These phenomena did not occur above 2.5 percent TVS.

Aeration/Oxygen Concentration. Experiments were conducted using both air and pure oxygen as the aerating gas to determine the benefits which might be derived from the use of pure oxygen. It was found that these two methods of aeration produced little, if any, difference in the observed organic reductions. Treatment with pure oxygen at high temperatures tended to produce high initial VSS reduction rates as shown in Figure 6.

Another process variation observed while comparing these two methods of aeration occurred at a treatment temperature of 31°C. At this temperature the process aerated with pure oxygen maintained a relatively high rate of oxygen uptake after the fifth day of aeration, as shown in Figure 8, while the oxygen uptake for the air process dropped sharply. In addition, the oxygenated process maintained a relatively diverse protozoa population while the only observed microfauna in the air treated sludge were rotifers. The stability test indicated that the air aerated sludge could be retained without aeration for significantly longer periods of time (after five days of aerobic treatment) than the oxygenated sludge without producing septic conditions.

Aerobic digestion was carried out at dissolved oxygen concentrations ranging from less than 1.0 mg/l to 35.00 mg/l. Dissolved oxygen concentrations below approximately 3 mg/l appeared to be detrimental to the aerobic digestion process.

The oxygen uptake varied with treatment temperature, solids concentration and detention time. At 42°C with initial solids concentrations less than 2.5 percent VS, and a three day detention time, the oxygen uptake was 240 mg/hr/gVS and the oxygen utilization was 2.20 mg of oxygen per mg of VSS destroyed. At 30°C with initial solids concentrations less than 2.5 percent VS and a 12.5 day detention time, the oxygen uptake was 9 mg/hr/gVSS and the oxygen utilization was 1.70 mg of oxygen per mg of VSS destroyed.

Sludge Stabilization

An indication of the relative stability of the sludge was obtained by incubating samples of the sludge at 37°C in air-tight BOD bottles while noting the time for septic conditions to develop. Since this test was carried out under conditions highly favorable for anaerobic metabolism, the times found for development of septic conditions should be less than would result in practice.

The aerobic treatment time required to achieve a relative degree of stability, as defined by the time for septic conditions to develop when the sludge was stored without aeration, varied with the temperature at which digestion was carried out and the solids concentrations of the feed sludge. For a given treatment temperature and initial solids concentration the relative degree of stabilization produced was found to be a function of the detention time. Although it was observed that different relative states of stability could be reached by a vriety of treatment methods, as shown in Appendix B, complete stability was most closely approached when the digestion was carried out at a temperature

of 30°C with an initial sludge volatile solids concentration of less than 2.5 percent. With these operating conditions, the process proceeded most rapidly and produced the most stable end product. As will be discussed in a later section, these operating conditions favored the development of a succession of those microorganisms that had the capability of producing a very stable sludge.

Samples submitted to the stability test were analyzed to determine if the initial sludge pH, oxygen uptake rate, or extent of nitrification affected the results. It was found that the results given by this test were not altered by initial sample pH values as low as five. Sludge oxygen uptake rates were commonly 10 mg/l/hr (2 mg/hr/gVS) after 15 days of aerobic digestion. With this rate of oxygen uptake and an initial dissolved oxygen concentration of 30 mg/l, the free available oxygen was taken up in approximately 3 hours. In other words, the sludge submitted to the stability test was without dissolved oxygen after three hours. Since some samples required as long as 60 days to develop septic conditions, it was concluded that the initial dissolved oxygen had little effect on the stability test results. Further, a series of samples that had been treated for from five to fifteen days all had a nitrated concentration of approximately 300 mg/l and yet, the time for septic conditions to develop varied from three to twenty days. Sludges processed at 42°C had essentially a zero nitrate concentration but were relatively stable if digested for 25 to 30 days. Thus, it was concluded that the nitrate concentration did not affect the stability test results.

It was also found that the initial rate at which the VSS

were destroyed did not indicated relative sludge stability. Sludges processed at temperatures ranging from 26°C to 50°C generally showed similar solids destruction rates but the sludge processed at a temperature of 29° to 31°C was always found to be the most stable (Appendix B).

In comparing the characteristics of numerous samples that were submitted to the stability test, (Appendix C) it was found that by processing a one percent solids feed sludge at 30°C, stability could be characterized by a carbon to nitrogen ration below 7.5 (carbon as measured by COD test, nitrogen as total nitrogen), a 30°C oxygen uptake rate of less than 5.0 mg/hour/g VSS, and a nitrate concentration of approximately 300 mg/l (the sludge pH being greater than five). The relatively low C/N ratio resulted from the loss of carbon as CO_2 while the nitrogen concentration was not significantly lowered unless a denitrification step was employed. A low oxygen uptake rate indicated that the sludge had either approached a stable state or that the reaction was being inhibited in some way, such as by a low pH or loss of viability.

It was found that with a feed sludge volatile solids concentration of one percent, aerobic digestion at a temperature of 30°C produced a very stable end product sludge as shown in Figures 13 and 14. These figures show the results for two separate continuous feed experiments. As can be seen, a very stable sludge resulted with a detention time of approximately 12.5 days.

The development of a stable sludge during aerobic digestion was readily identified. The settling characteristics, odor and color of the sludge changed dramatically. A very earthy odor would develop.

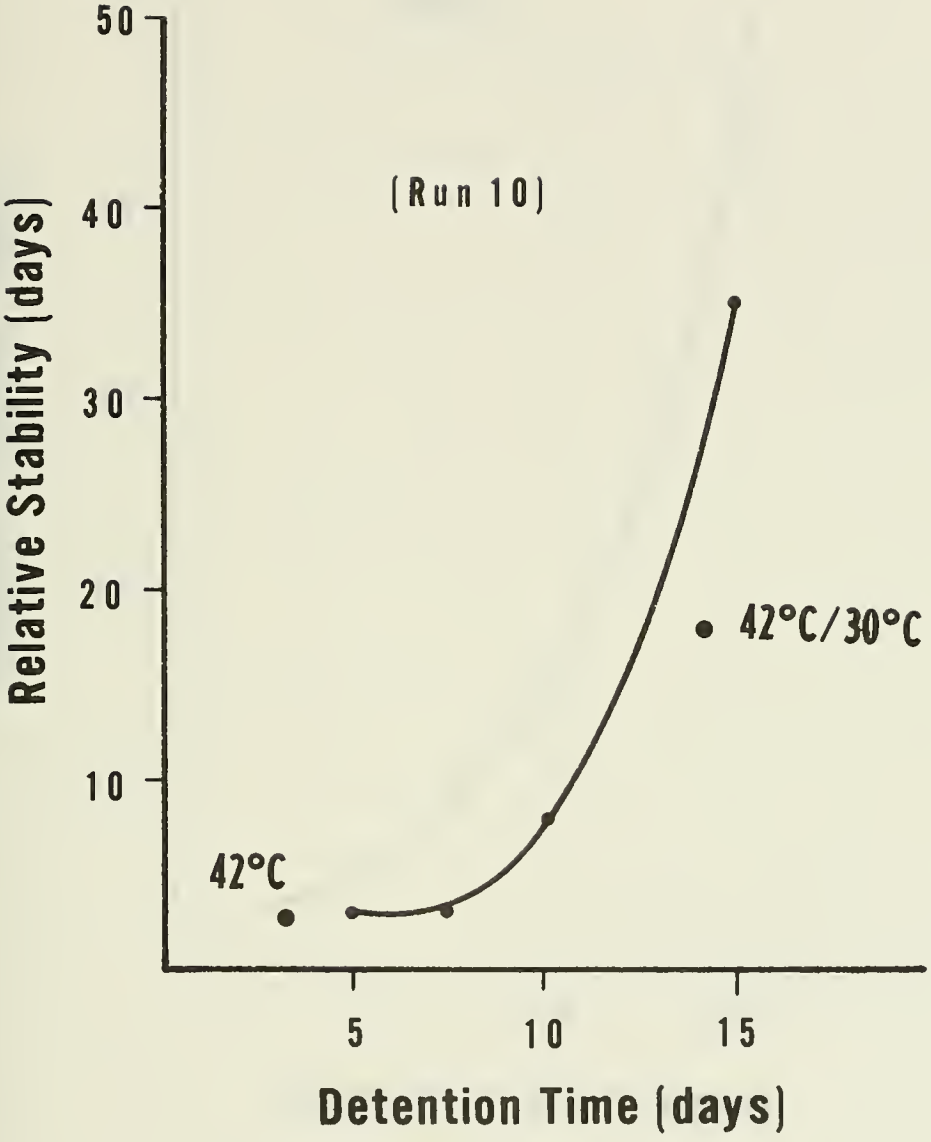

Figure 13

Sludge Stability as a Function of Detention (30°C)

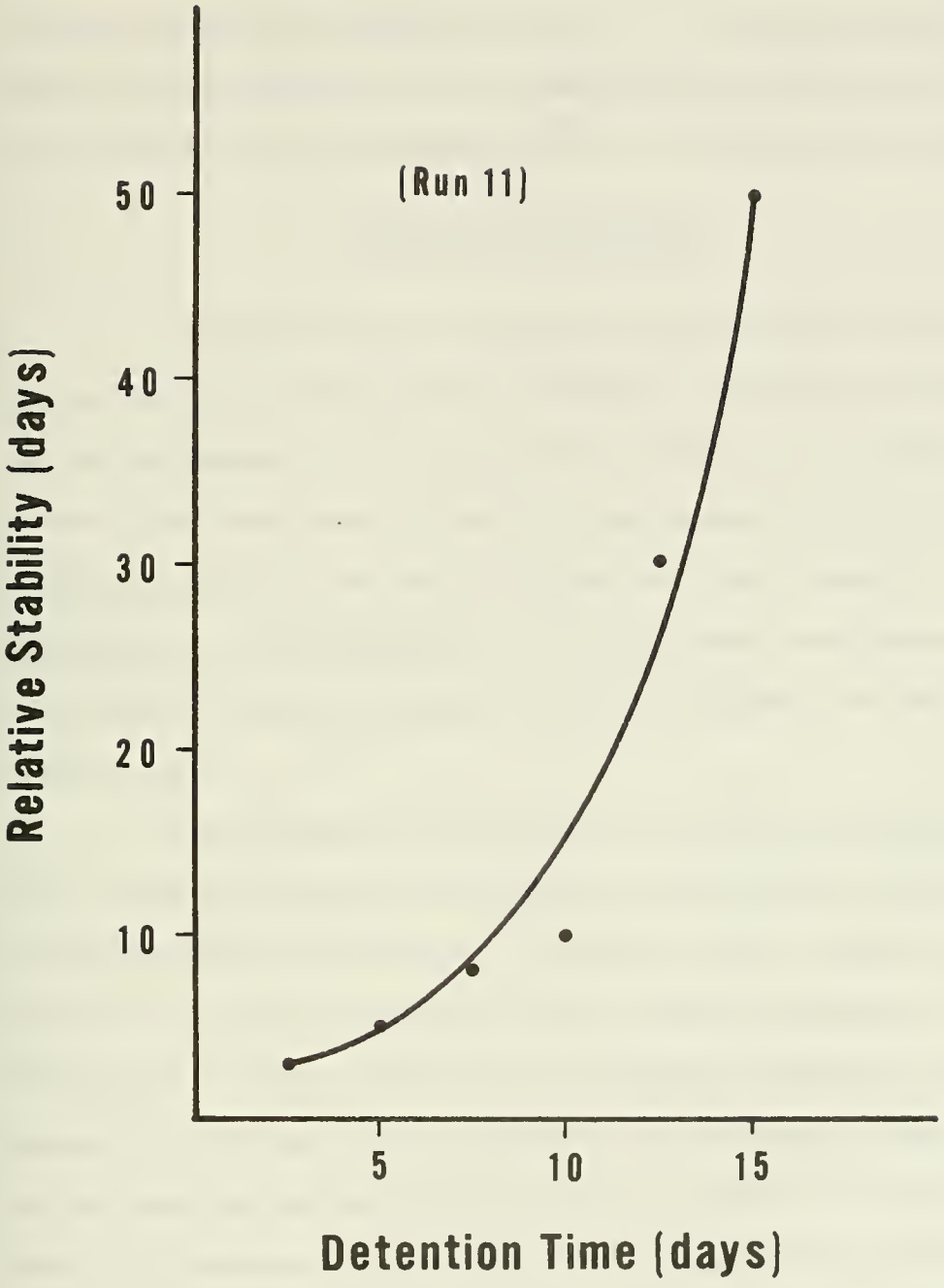

Figure 14

Sludge Stability as a Function of Detention Time (30°C)

The rate at which the solids settled would show a rapid improvement and the sludge took on a rather dark brown color. These characteristics were only observed when the feed sludge VS concentration was held below 2.5 percent and the process was carried out at approximately 30°C.

Microscopic Examination

The initial protozoa populations of the waste activated sludge samples as it came from the waste treatment plant were not constant but varied seasonally, and were highest during the cold, winter months. The summer waste activated sludge generally had a population of Vorticella, while the winter sludges had a high number of Aspidisca and some Vorticella. The winter sludges settled well and when digested were the sludges for which the highest VSS destructions were obtained.

Protozoa populations similar to the feed sludge populations were developed during aerobic digestion of the waste activated sludges at temperatures less than 31°C. When batch aerobic digestion was carried on at 40°C to 42°C, the initial protozoa population disappeared within six hours and a new growth of Monadidae protozoa appeared after three days of aeration. For the batch process, this new protozoa population would remain in the sludge for only 24 to 48 hours. The occurence of these protozoa corresponded to measured peaks in the rate of oxygen uptake. Both the high Monadidae population and the high rate of oxygen uptake (240 mg/hr/gVS) were maintained under the continuous feed conditions with a three day detention time. As was previously discussed, a rapid destruction of the VSS resulted at 42°C.

Rotifers developed in the sludge during both batch and continuous feed aerobic digestion at temperatures of less than 31°C. These microorganisms developed in the batch processed sludge within five to ten days of aeration when a feed sludge concentration less than 2.5 percent VS was processed at temperatures of 29° to 31°C. Processing under these conditions for ten days produced a well stabilized sludge which settled rapidly to approximately two and one half percent solids. Sludges processed under conditions that were not conducive to the development of rotifers (temperatures) above and below 29° to 31°C and feed sludge solids levels above 2.5 percent) required a longer treatment time and did not produce the stable sludge. Using the 29° to 31°C temperature range and feed solids of less than 2.5 percent, it was found that significant rotifer populations would develop under continuous feeding. In fact, rotifer populations of 50,000 organisms per liter were observed (Figure 17). These rotifers were never observed in the sludges which had been heated to temperatures above 31°C.

Species diversification varied during aerobic digestion. Elevated temperature and high solids concentrations were found to limit the diversity of the protozoa population. In addition, each of the six reactors which were fed in series was found to have a less diverse protozoa population than reactors fed fresh sludge. Fauna diversity decreased as digestion progressed.

Microfauna Density

The number of protozoa that developed during the aerobic digestion of the waste activated sludge varied with treatment time,

temperature and solids concentration. In addition, the population varied with the condition of the feed sludge. Shown in Figure 15 are the protozoa densities observed during the 31°C batch aerobic digestion of a waste activated sludge which had no initial protozoa population. The number of protozoa quickly peaked after 48 hours of aerobic digestion and then slowly declined. As has been discussed, this protozoa population coincided with an increase of the oxygen uptake rate.

When aerobic digestion was carried out at temperatures of 40 to 42°C, the initial feed sludge protozoa population disappeared. After approximately three days of treatment, a very large population of Monadidae protozoa appeared. For the typical results shown in Figure 16, no protozoa were observed during the first 63 hours of aeration. After 63 hours, a significant population of protozoa appeared which peaked after 91 hours of aeration at approximately 3.7×10^5 organisms/liter. These protozoa disappeared after 144 hours of aeration. This peak Monadidae population coincided with the peak oxygen uptake of 240 mg/hr/gVS.

The same phenomenon, as shown in Figure 16, was observed for a feed sludge having an initial protozoa population of 8.7×10^3 organisms/liter. When aerobic digestion was carried on at temperatures of 26° and 29°C, the populations rose to peaks of 3.5×10^5 organisms/liter after 45 hours of aeration. These peaks corresponded to peaks in the rate of oxygen uptake of 117 mg/l/hour after 1.2 days of aeration and 90 mg/l/hour after 2 days of aeration. When aerobic digestion was carried on at a temperature of 41°C for 48 hours, the populations rose to peaks of 1.9×10^5 and 3.6×10^5 organisms/liter

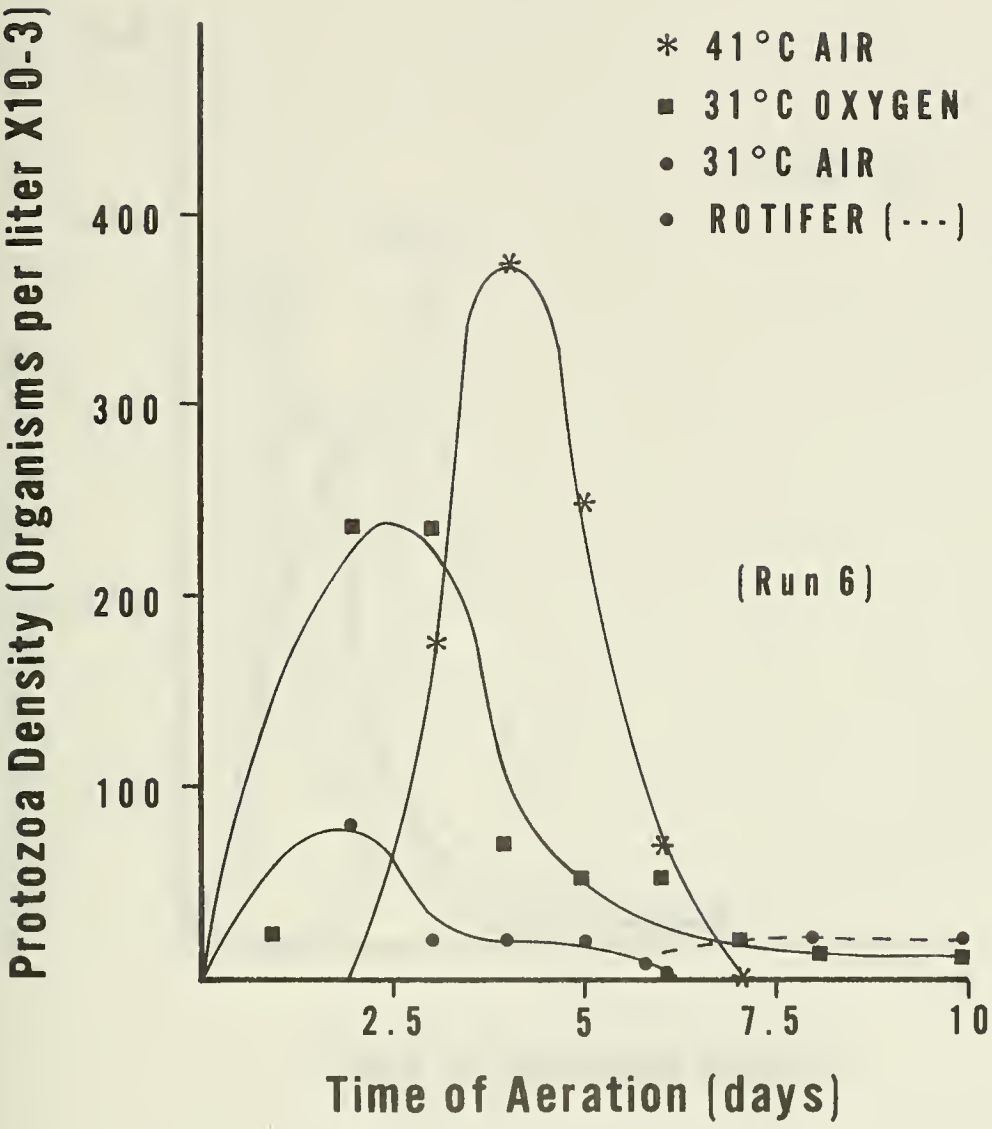

Figure 15

Protozoa/Rotifer Population
Changes During Stabilization at 31°C and 41°C

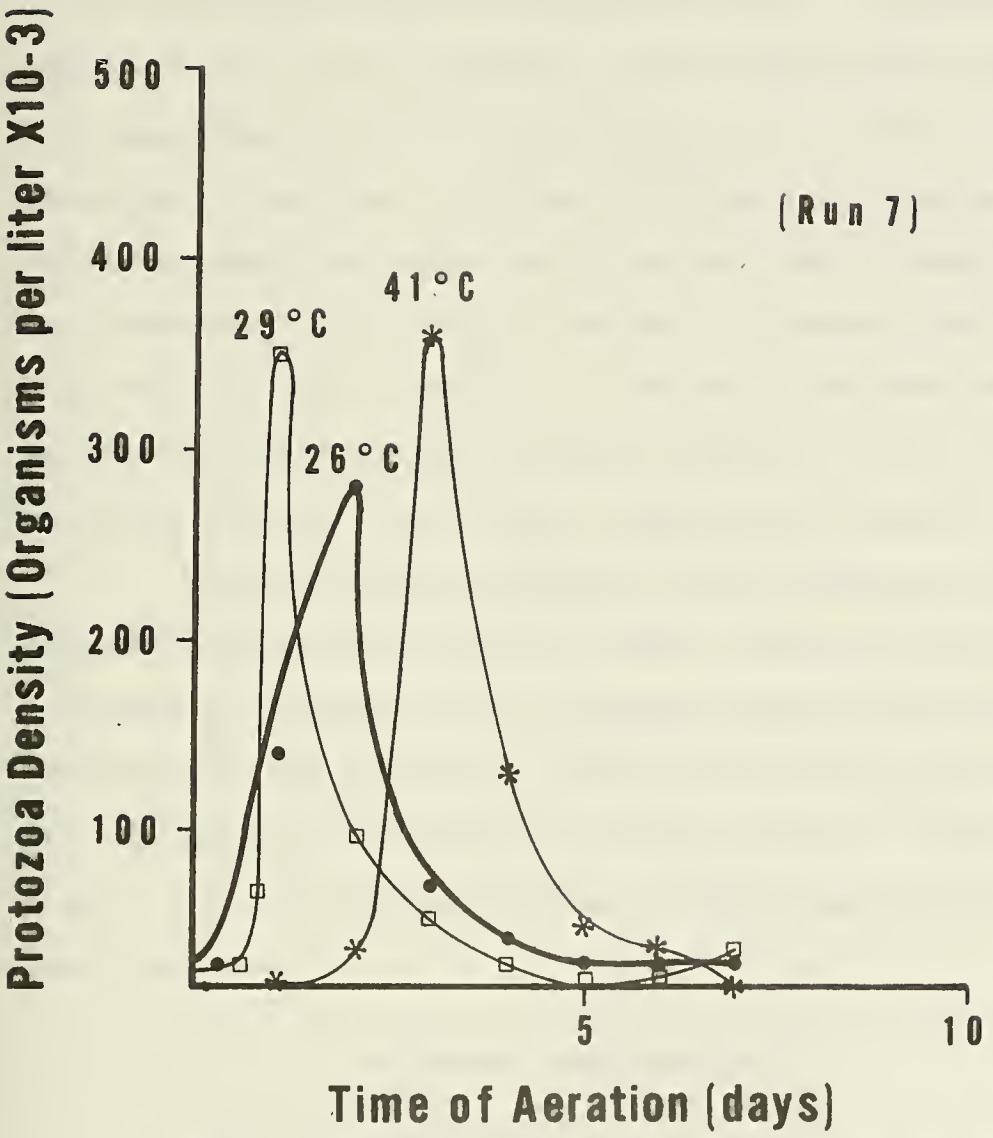

Figure 16

Protozoa Population Changes During Stabilization at 26°C, 29°C and 41°C

at 72 hours and then fell to nearly zero after 144 hours of aerobic treatment.

The rotifer population was more sensitive to temperature and solids concentration than the protozoa population. Under batch conditions the rotifers appeared only when digestion was carried out at a temperature of 29 to 31°C on a sludge with an initial solids concentration of less than 2.5 percent TVS. These microorganisms did not develop in significant numbers under the batch mode of operation. They were observed after five days of aeration, but generally did not appear until after ten days of aeration. It was found that these rotifers provided a reliable indicator of sludge stability in that their appearance indicated that a stable sludge had been produced.

With the continuous feeding, rotifer populations of up to 50,000 organisms per liter were observed. Figure 17 shows rotifer density as a function of treatment time for continuous feed operating conditions. Significant rotifer populations existed at each stage of the process with the peak occurring after 2-1/2 days of aeration. These rotifers were found to be the predominant microfauna in this sludge after only five days of aeration.

Microfauna Identification

General characteristics of the protozoa, such as mobility and method of feeding provided valuable indicators of the general microbiological condition of the sludge and aided in the identification of certain optimum operating conditions. Identification was generally carried to the family level for the predominant microfauna by microscopic

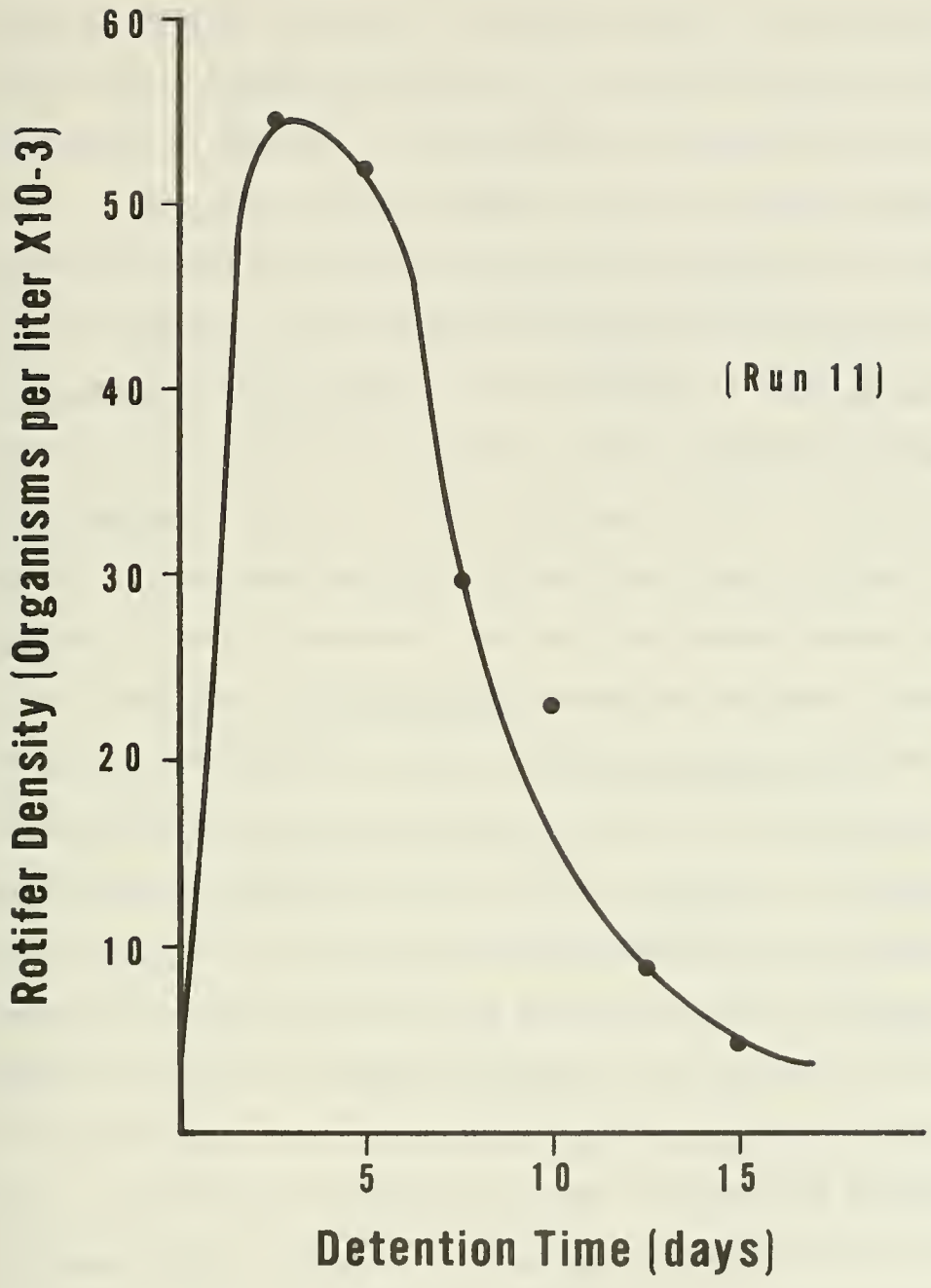

Figure 17

Rotifer Population as a
Function of Detention Time at 30°C

observation, measurement, drawings, and photographs. This information was then compared with that for specimens common to this type of environment. Valuable assistance in the identification was obtained from Doctor J. Bushnell of the University of Colorado Biology Department.

The waste activated sludge used in this study could generally be characterized on the basis of its protozoa population as either (1) protozoa free, (2) predominantly Aspidisca(3) equal populations of Aspidisca and Vorticella, or (4) predominantly Vorticella. Other ciliates infrequently were observed, such as Paramoecium, Colpoda, Tintinnediun, but never as the predominant form. As was previously stated, the protozoa population of the feed sludge provided a good indicator of the VSS reductions that could be expected during digestion. It was found that a high Aspidisca population indicated a potential for a high VSS reduction, while a high Vorticella population indicated that relatively low reductions were likely to be forthcoming. When the sludge was submitted to batch aerobic digestion at temperatures of less than 31°C and initial solids concentrations of less than 2.5 percent TVS, the fauna population evolved through a predictable pattern which was found to be somewhat dependent upon the characteristics of the feed sludge. For a feed sludge which was initially "protozoa free", a population of Colpoda with some free swimming Vorticella developed within 27 hours. The Colpoda disappeared after 9 hours of aeration leaving the free swimming Vorticella. These organisms then evolved into sessile types which were observed through the remainder of the experiment. Bdelloid rotifers were observed in sludges processed at 29°C after 120 hours of aeration (dashed line Figure 14). When the feed sludge has an initially large Aspidisca population, it was

found that these protozoa would decline slowly during the first 56 hours of aeration and were then replaced by the sessile Vorticella forms. The Vorticella population would then slowly decline during the next 57 hours of aeration. The Bdelloids appeared after 137 hours of aerobic treatment. For a feed sludge with approximately equal initial populations of free swimming Vorticella and Aspidisca, it was found that the Aspidisca population declined while the Vorticella population increased and peaked after 91 hours of aeration. The free swimming forms then gradually evolved into the stalked forms which were present to the end of the experiment along with some rotifers. The population dynamics described above are summarized and shown graphically in Figure 18.

Sludges with solids levels of 2.5 to 3.5 percent VSS developed populations of the sessile forms of Vorticella, at treatment temperatures of less than 31°C. Often large populations of these organisms would develop (2.6×10^8 organisms/liter) within 24 hours of aeration. This population then gradually declined and after 216 hours of aeration, a new population of Colpoda would appear and remain to nearly the end of the experiment.

When a feed sludge was submitted to aerobic digestion at a temperature of 40 to 42°C, the initial protozoa population would quickly disappear and a completely new protozoa population would develop. Under these operating conditions the protozoa in the feed sludge disappeared within three to six hours of aeration and after approximately three days (Figure 14), a large population of Monadidae protozoa appeared. Under batch conditions, these organisms developed

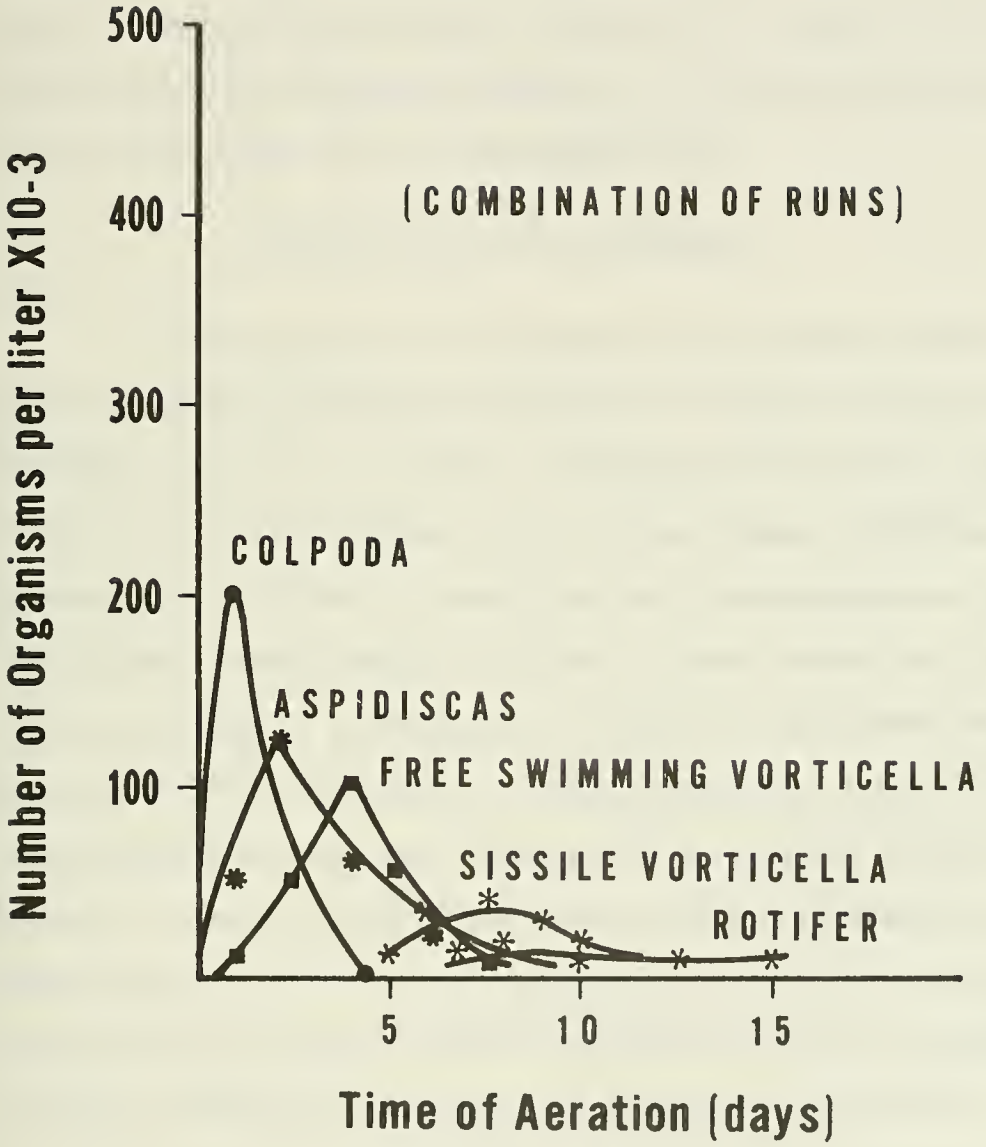

Figure 18

Microfauna Population Dynamics During Batch Aerobic Digestion at 30°C

very quickly, producing very large populations which then quickly disappear after an additional 48 hours of aerobic treatment. These small protozoa were the only microfauna seen when aerobic disgestion was carried out at 40 to 42°C. They did not develop when the sludge solids concentration was above 2.5 percent VSS. Rotifers were never observed at these operating temperatures nor did they ever develop in any sludge which had been heated above 31°C.

Secondary Bacteria Predominance

During several of the experiments at elevated temperatures secondary bacteria growths were observed or strongly implicated. Secondary bacterial development was indicated during aerobic digestion at 50°C by the sharp increases in the sludge oxygen uptake that occurred after 72 hours of aeration without the appearance of any new protozoa. These peaks in the rate of sxygen uptake were thus taken as evidence of a new growth of bacteria. Pasteurized samples digested at 30°C showed peaks in oxygen uptake rates after 44 hours of aeration which, in this case, corresponded to observed growths of bacteria. None of the new bacteria were observed 12 hours before or 44 hours after this observation. An observed growth of the same bacteria occurred after 93 hours of aerobic digestion at 40°C. No evidence was found indicating that these bacteria enhanced the process.

Organic Nitrogen Transformations

The biological decomposition of the organic nitrogen resulted in an increase in the alkalinity concentration of the sludge.

It was found that this decomposition increased the alkalinity at the rate of three to five mg per mg of organic nitrogen destroyed. Nitrification, on the other hand, was found to consume alkalinity at the rate of seven mg per mg of ammonia destroyed. Therefore, overall aerobic digestion process was found to be alkalinity consuming. With a feed sludge of approximately one percent TVS, the organic nitrogen rduction was found to be approximately 60 percent and additional alkalinity of approximately 1000 mg/1 was required to maintain a favorable pH.

Figures 19, 20 and 21 show the changes in the pH, alkalinity and ammonia values brought about by aerobic digestion of a sludge sample at four different temperatures. At treatment temperatures of 26°C and 29°C, the trends shown by the pH values were found to be similar to those of the alkalinity values and both were found to indicate the relative degree of ammonification and nitrification. If there had been no nitrification during the digestion of this sludge, all ammonia concentrations would have been at least equal to the maximum value shown for treatment at a temperature of 41°C. It can be seen that the ammonia concentration in the sludge digested at 29°C began to decrease first and continued to decrease until the pH reached 4.7. The rise in the pH for this sludge, after 15 days of treatment indicated that the nitrification process had been retarded to the point that it was once again being exceeded by ammonification. After 16 days of aeration, the pH of this sludge was raised to 7 and the alkalinity to 600 mg/1 by the addition of $NaHCO_3$. Nitrification then proceeded until the ammonia concentration reached 1.6 mg/1, the

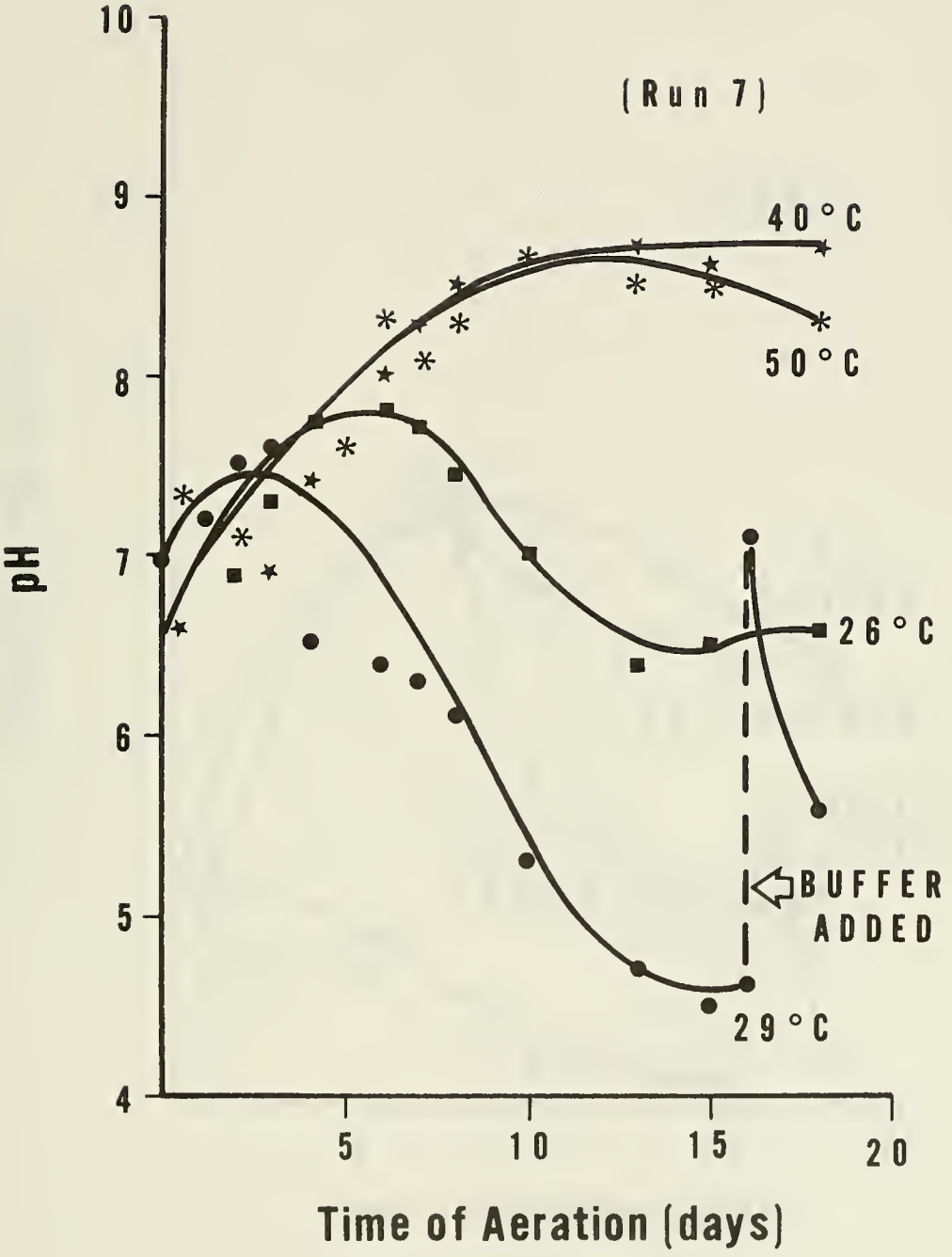

Figure 19

Changes in pH During Batch Aerobic Digestion at 26 °C, 29 °C, 40 °C and 50 °

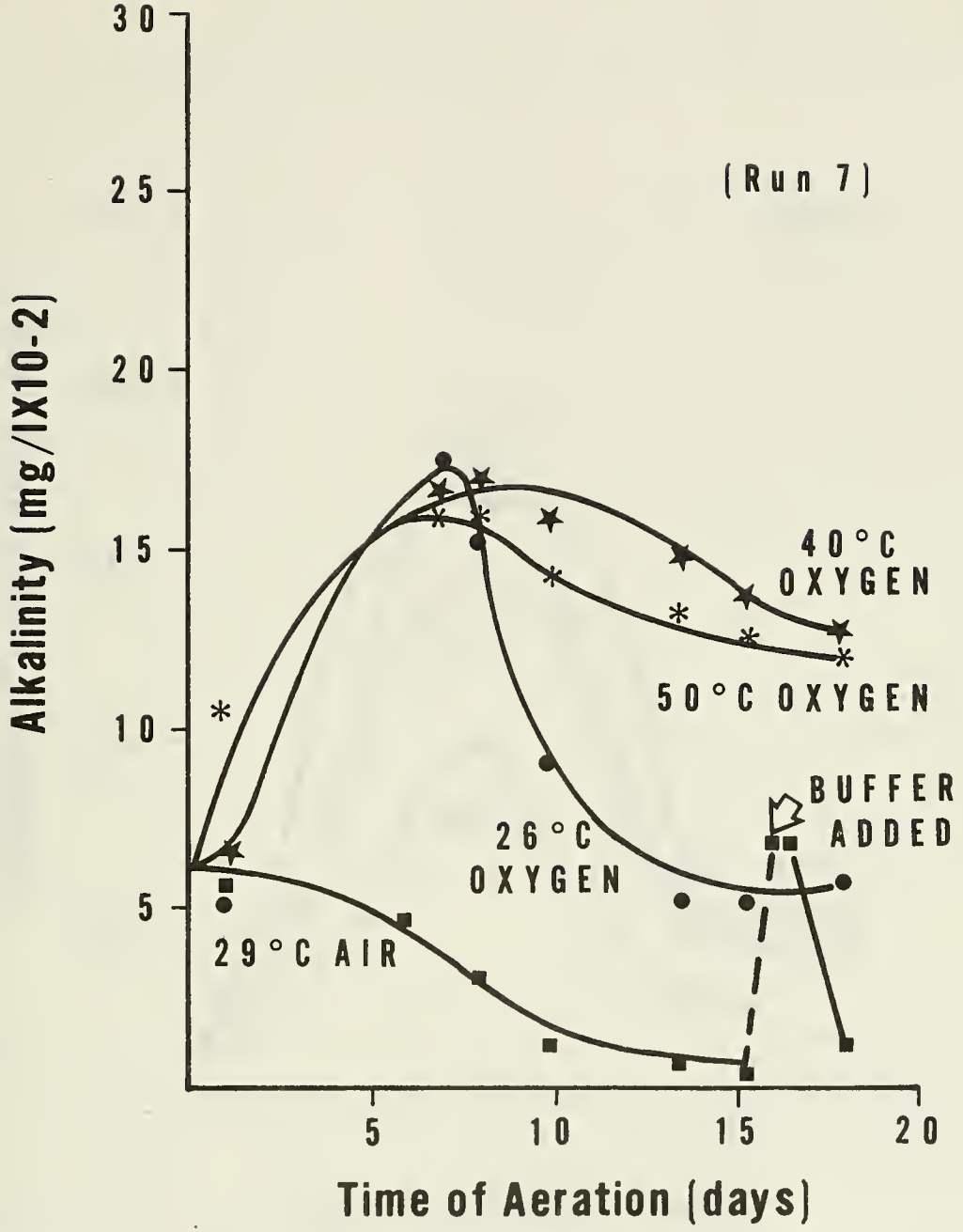

Figure 20

Changes in Alkalinity During Batch Aerobic Digestion at 26°C, 29°C. 40°C and 50°C

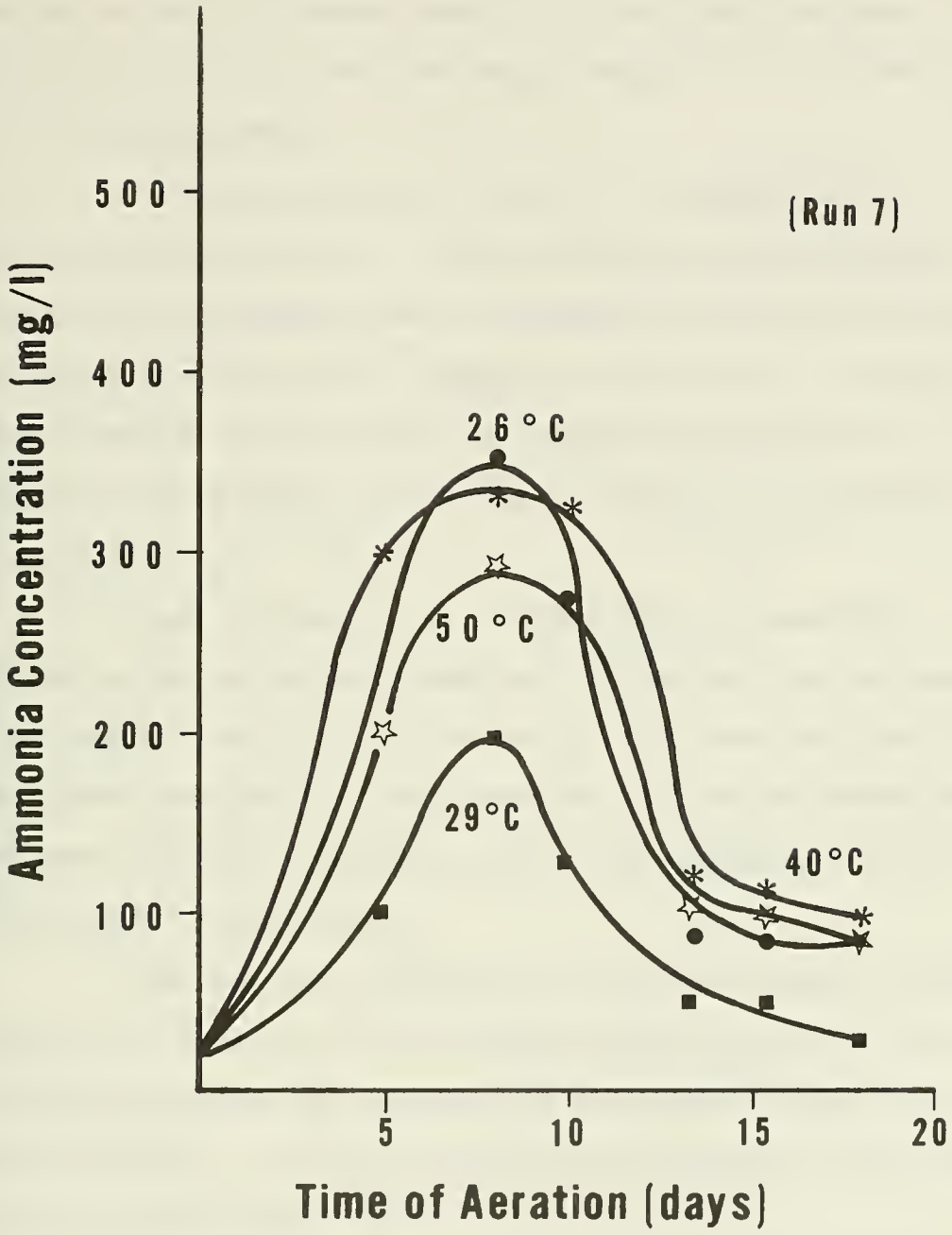

Figure 21

Changes in Ammonia During Batch Aerobic Digestion at 26 °C, 29 °C, 40 °C and 50 °C

the pH 4.9 and the alkalinity 64 mg/l (these values are not shown). Thus, with an initial volatile solids concentration of approximately one percent and a 60 percent reduction in the organic nitrogen, 1176 mg/l of alkalinity was supplied to complete the nitrification of the available ammonia.

The pH and alkalinity values at 40°C and 50°C did not drop as rapidly as at 30°C. However, significant ammonia losses suggested that an ammonia removal mechanism other than nitrification was active at these elevated temperatures and pH values. A strong ammonia odor was present under these operating conditions which suggested that stripping was the removal mechanism at the elevated temperatures.

Shown in Figure 22 are the alkalinity concentrations obtained during the aerobic digestion of sludges with solids concentrations ranging from 0.4 to 3.5 percent TVS. The relatively high alkalinities maintained in the sludges with high solids concentrations indicated that the nitrification reaction was inhibited at solids levels above 2.3 percent TVS.

There was some evidence that the dissolved oxygen concentration may have affected the nitrification process. Figure 23 shows the alkalinity values for aerating with air and pure oxygen during aerobic digestion. The best nitrification was obtained at 30°C using air as the aerating gas.

Initially the nitrogen in a waste activated sludge was essentially all in the organic form. The first five days of aerobic digestion were characterized by a rapid breakdown of the organic nitrogen and a rapid increase in the nitrite and nitrate concentrations

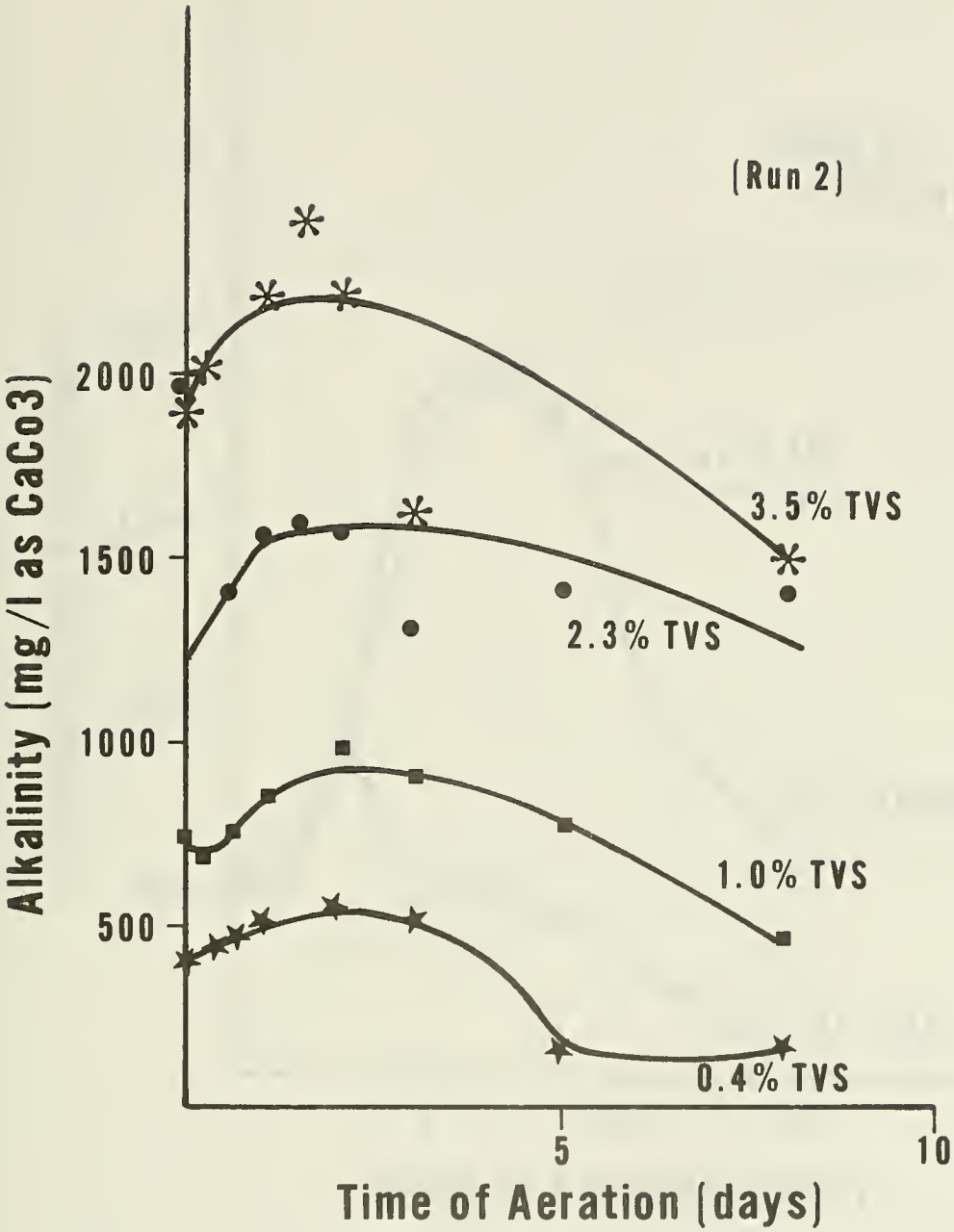

Figure 22

Changes in Alkalinity During Batch Aerobic Digestion at 0.4, 1.0, 2.3 and 3.5% TVS

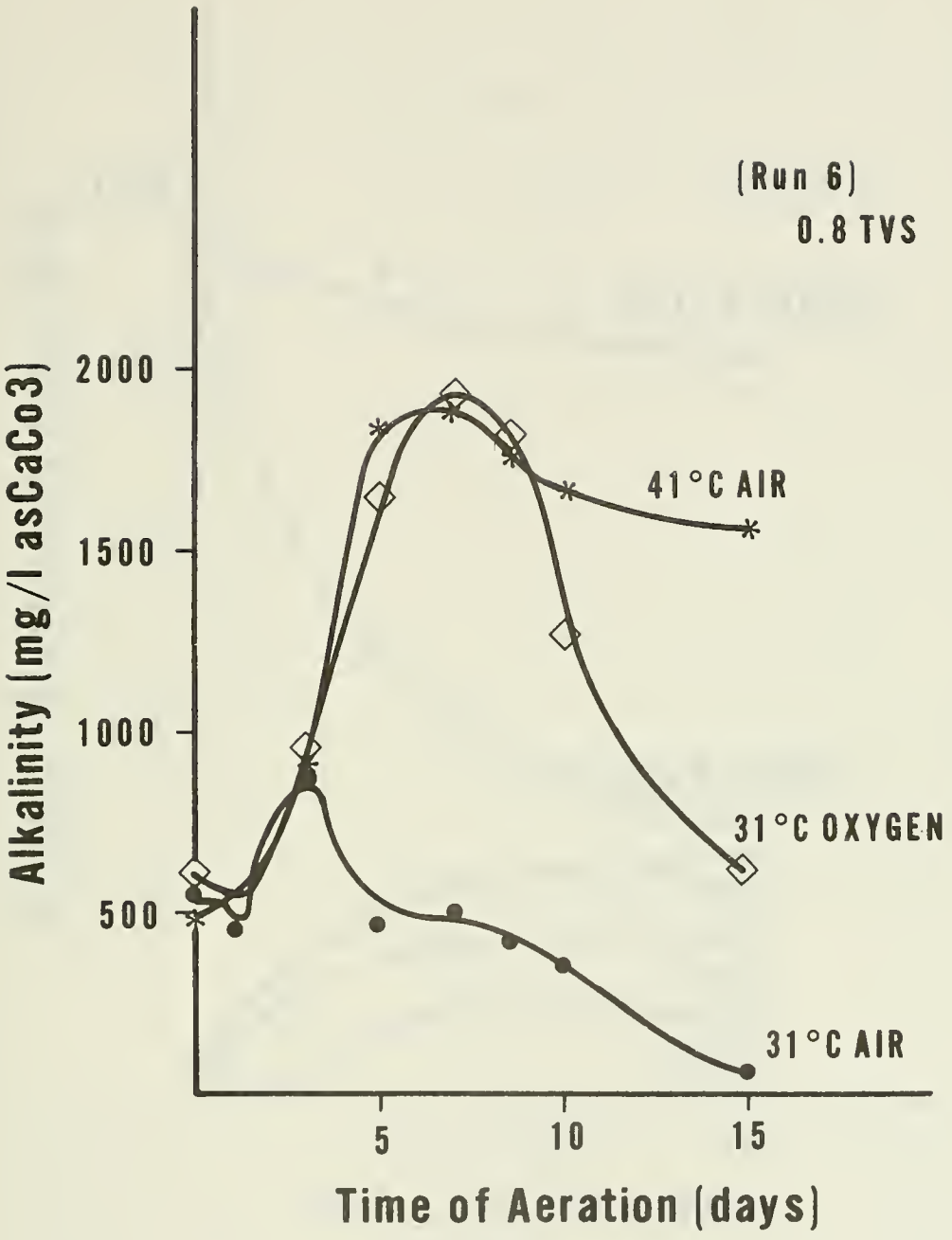

Figure 23

Alkalinity Variation During Batch
Aerobic Digestion at 31°C and 41°C

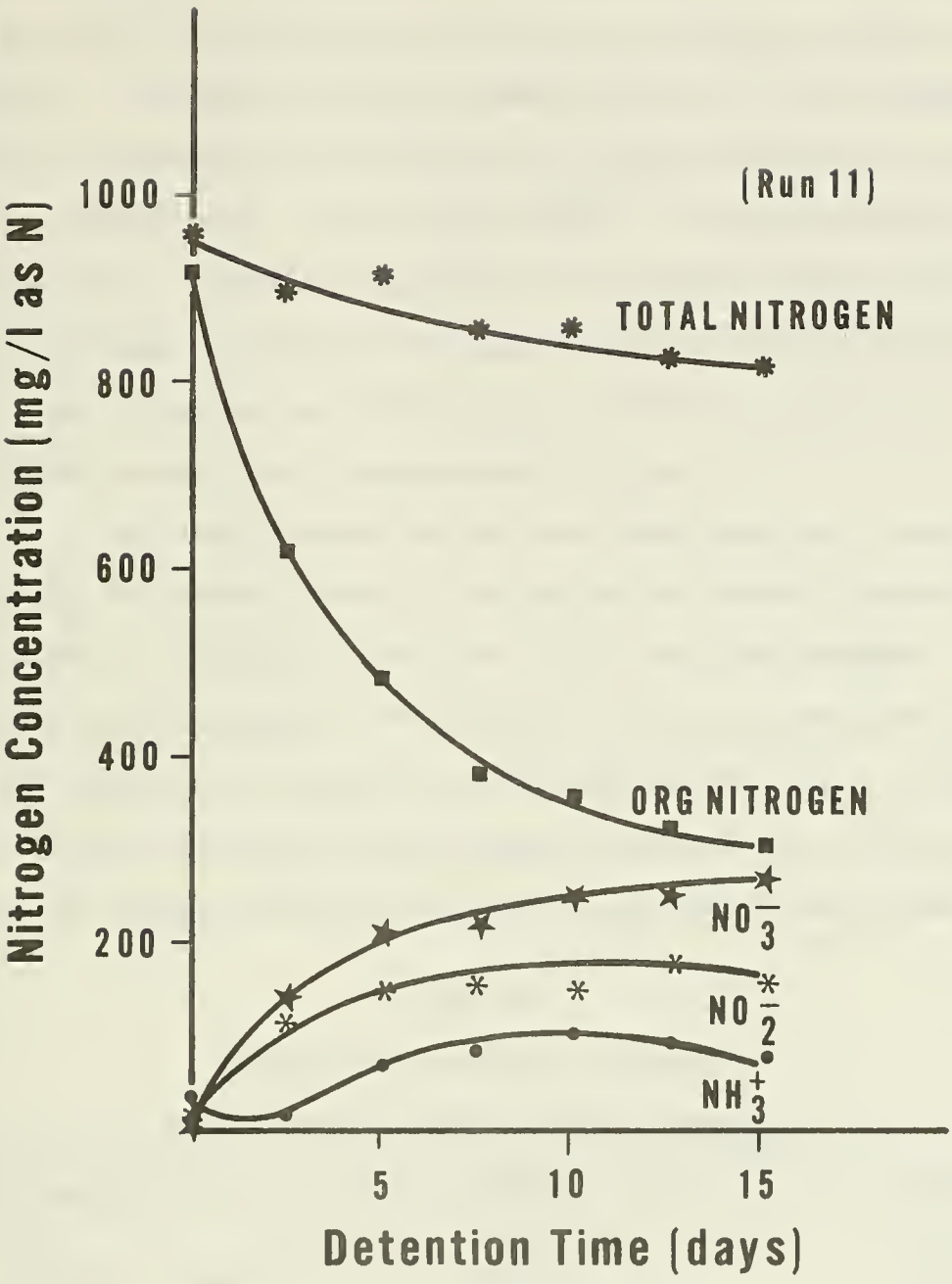

Figure 24

Changes in Forms of Nitrogen During Aerobic Digestion at 30°C

as shown in Figure 24. The first 2-1/2 days of aerobic digestion produced a nitrite concentration of 120 mg/1 and an ammonia concentration of 20 mg/1. The low pH after 2-1/2 days of aeration, as shown in Figure inhibited the nitrification reaction to a greater degree than the decomposition reaction and thus, resulted in an increase in the alkalinity and a rise in the pH value. For this experiment, approximately 2300 mg/1 of alkalinity was consumed through nitrification. Again, additional buffering of approximately 1000 mg/1 was required to complete the nitrification, and thus, to reduce the nitrogen concentration to approximately 300 mg/1.

The dentrification process was investigated as a means of reducing the nitrogen content of the sludge and also as a means for increasing the alkalinity and pH of a sluge that had undergone partial aerobic digestion. The dissolved oxygen concentration in one of the digesters was reduced to nearly zero for 24 hours to determine the changes resulting from brief periods without oxygen. Table IV shows the changes resulting from this 24 hour oxygen limited test.

TABLE IV

CHANGES RESULTING FROM 24 HOURS

WITHOUT OXYGEN DURING AEROBIC DIGESTION

Parameter	Before	After
pH	4.9	7.6
Alkalinity, $CaCO_3$	88 mg/1	630 mg/1
Settling	210 ml	500 ml
Organic - N	403 mg/1	466 mg/1
NH_3 - N	77	113
NO_3 - N	250	106
NO_2 - N	92	41
Total - N	822	726

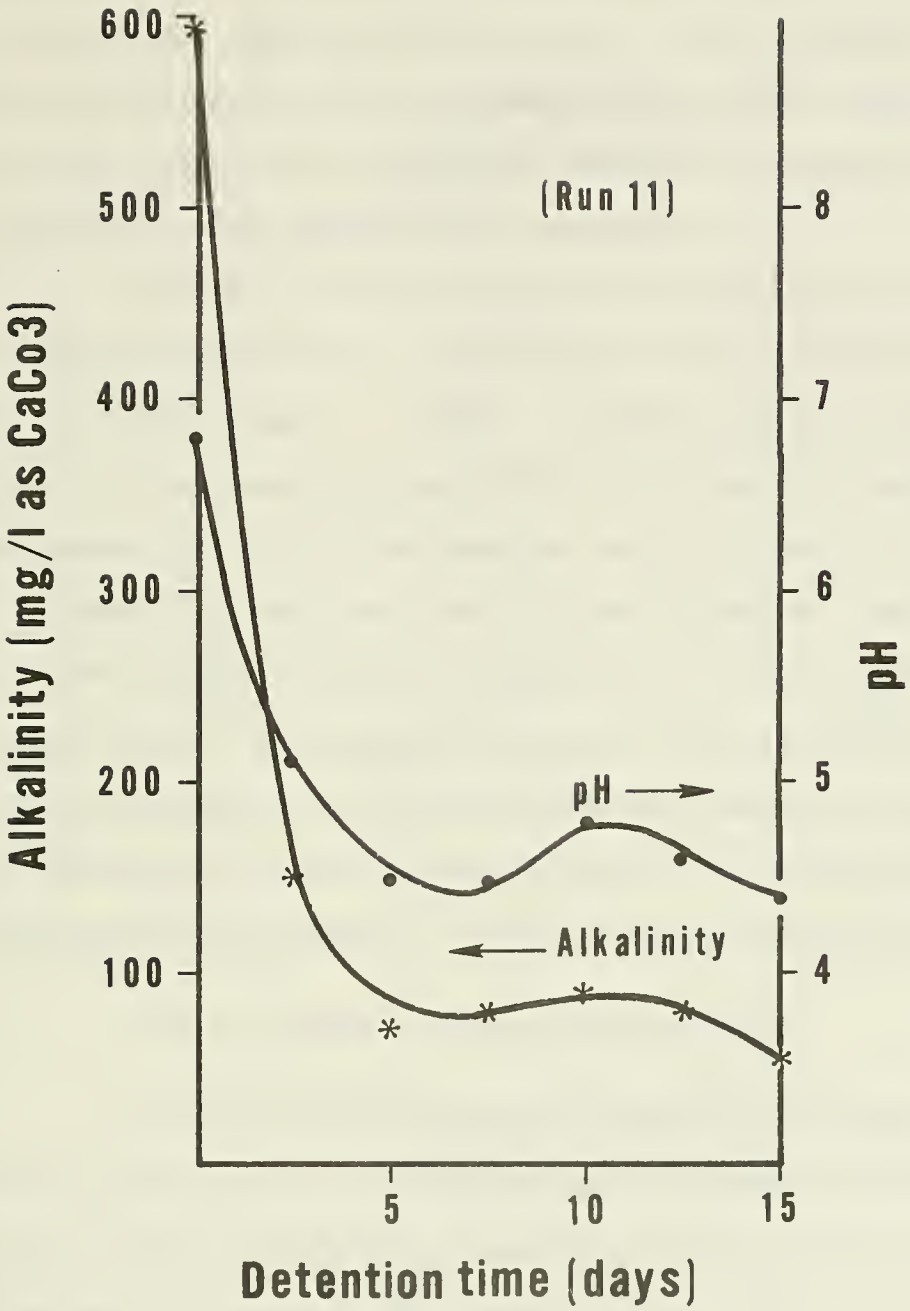

Figure 25

Alkalinity and pH Changes During Aerobic Digestion at 30°C

Rapid denitrification occurred resulting in a sharp increase in alkalinity and pH. Since the microorganisms that use nitrate as a final electron acceptor also thrive under aerobic conditions, rapid denitrification can be obtained with the aerobic sludge. As can be seen, this brief period without aeration also resulted in a degredation in the sludge settling properties.

In order to take advantage of the denitrification process as a source of alkalinity, a denitrification reactor was inserted into the aerobic digestion process. An aerobic digestion process with a 7-1/2 day detention time (30°C) was followed by a denitrification process with a 2-1/2 day detention time (30°C) which, in turn, was followed by another five days of aerobic digestion. Figures 26 and 27 show changes in pH and alkalinity and a nitrogen balance for this process. Approximately 67 percent of the available nitrate/nitrite concentration was utilized during dentirigication, resulting in an alkalinity increase of nearly 600 mg/l. The settling properties of the sludge again changed as a result of the period without aeration.

Solids Separation and Supernatant Quality

The settling characteristics of aerobically digested sludge varied and were found to be dependent upon the treatment temperatures, the feed solids concentration, the aeration time and the microbial population of the sludge. The sludge interface heights recorded after the one hour settling test are presented in Figure 28 as a function of aeration time. Only two aerobic digestion temperatues, 31 and 42°C, produced sludges that exhibited desirable settling properties. After

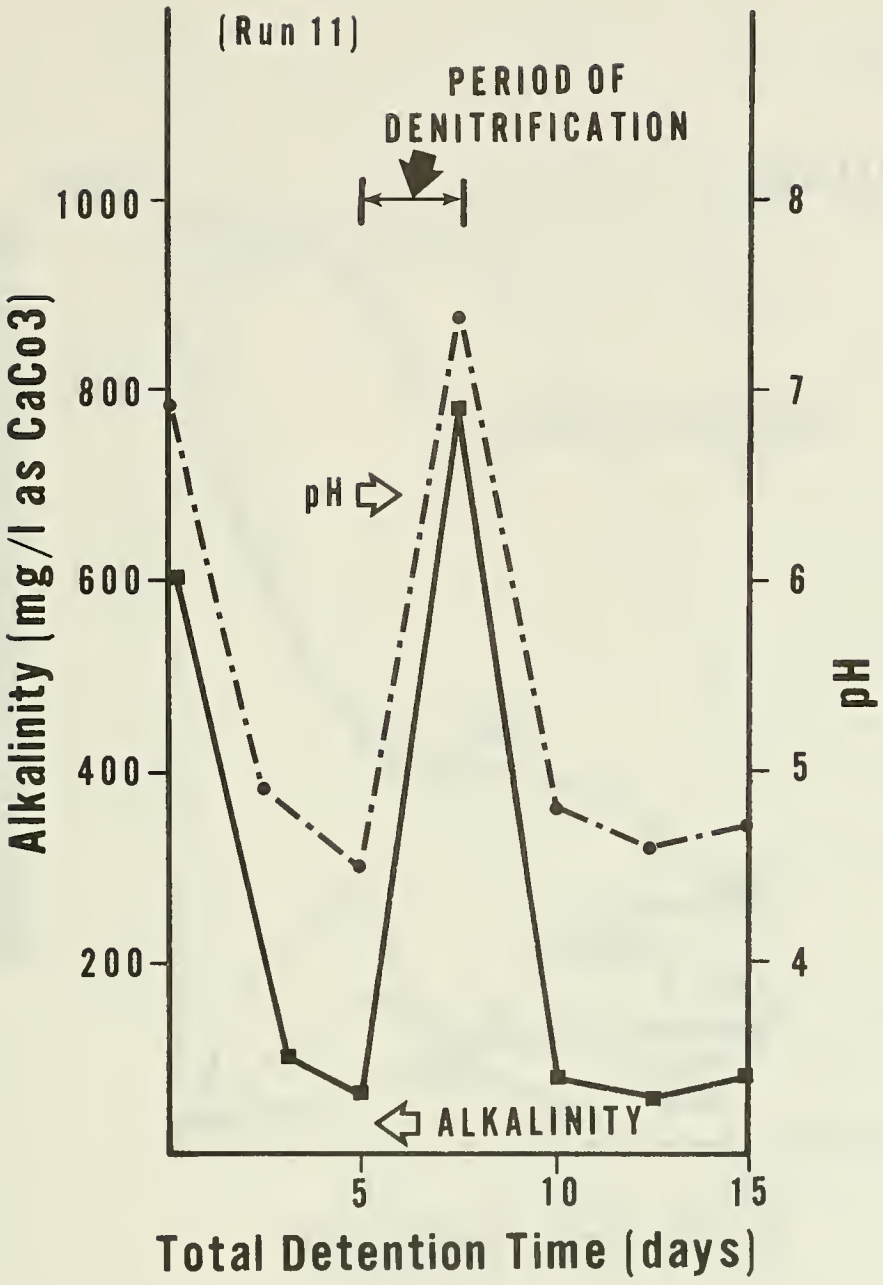

Figure 26

Alkalinity and pH Changes From Combined Nitrification / Denitrification Process at 30°C

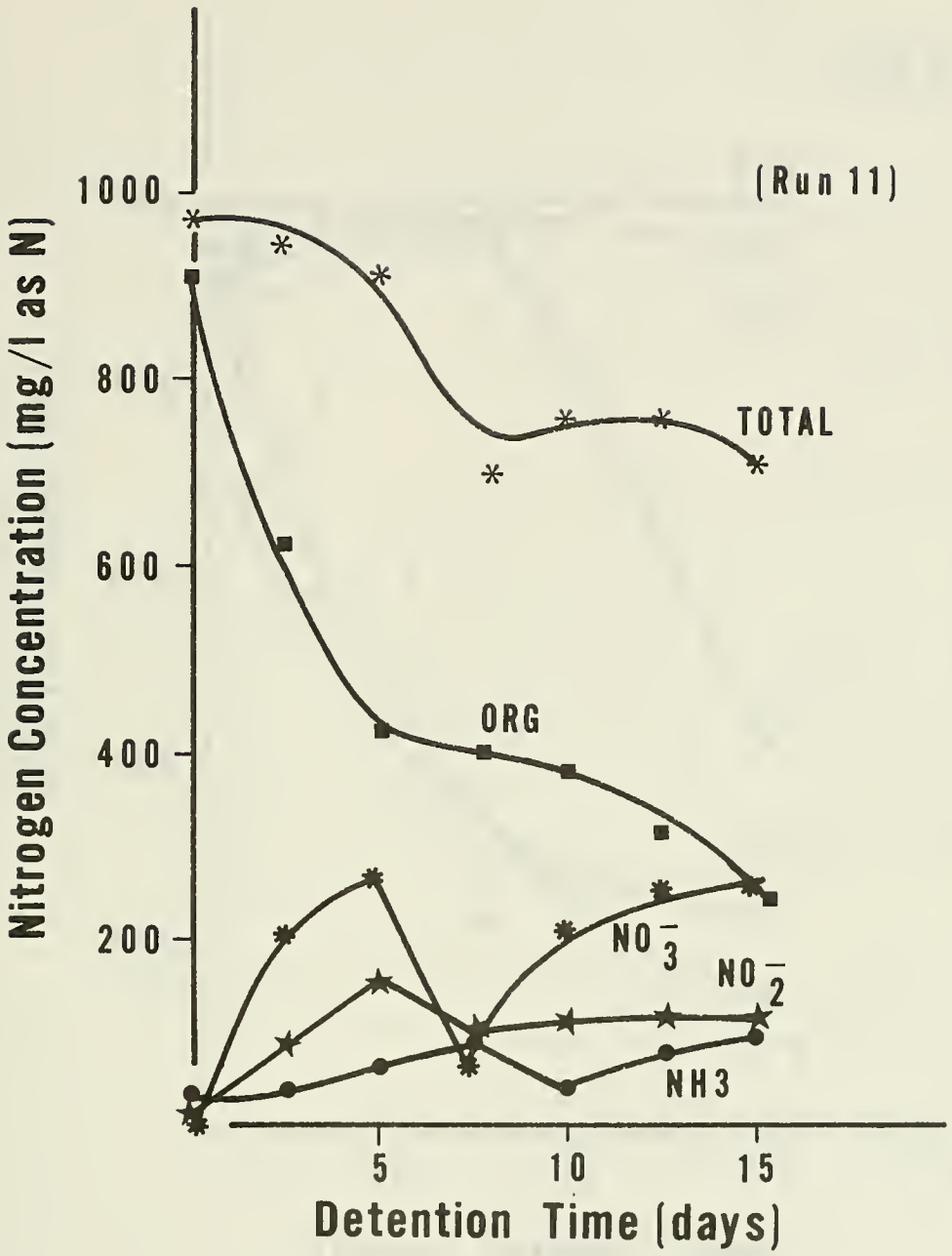

Figure 27

Nitrogen Balance During Nitrification/
Denitrification Process at 30°C

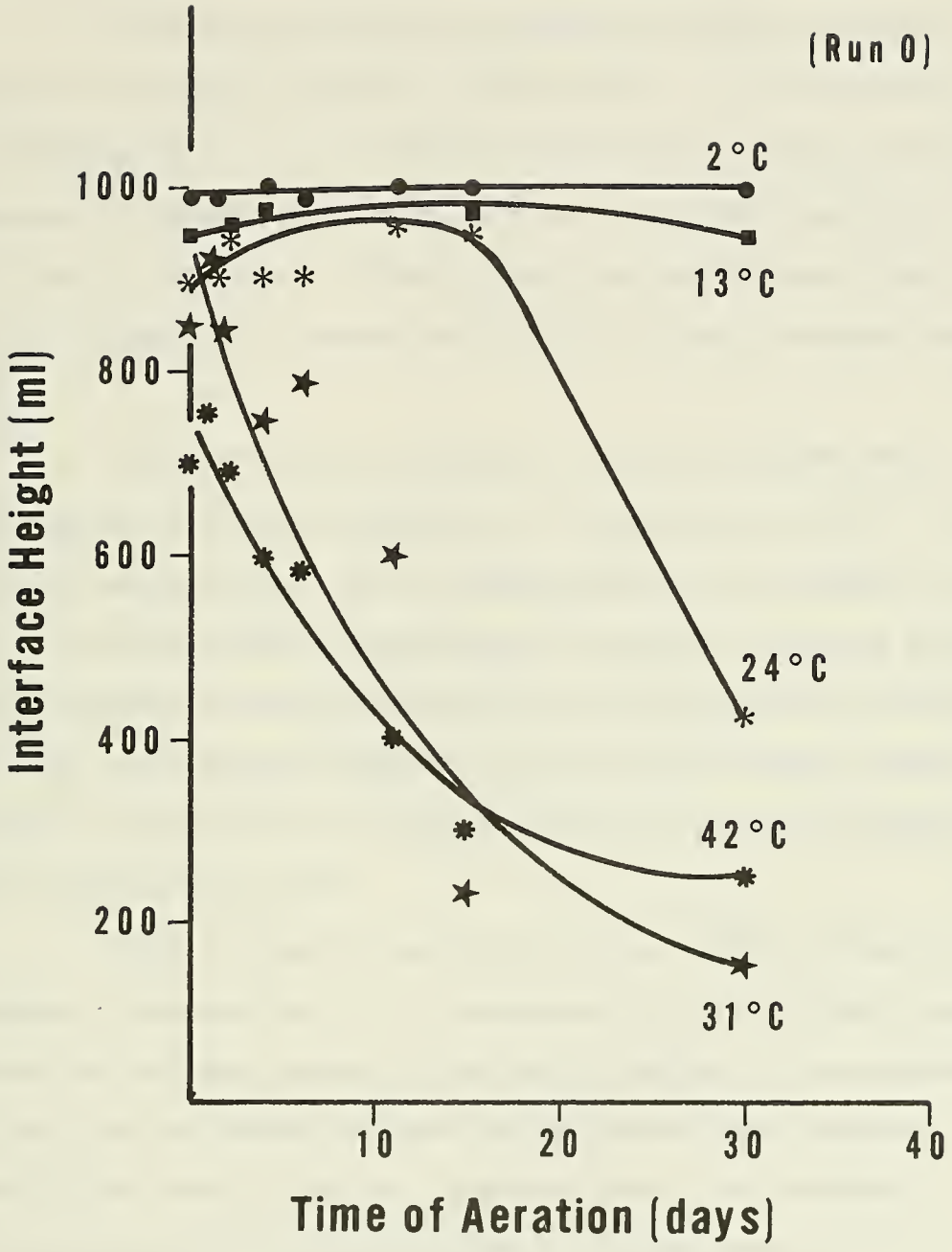

Figure 28

Temperature Effects on Aerobic Sludge Settling Characteristics

15 days of aerobic digestion, a sludge was produced that would settle from approximately 0.5 percent to 2.5 percent suspended solids.

The sludge produced by digesting at 31°C was different in physical appearance and settling characteristics than that produces by digesting at 41°C. At 31°C the sludge solids were dark brown and granular in appearance, while at 41°C the solids were light brown and fluffy in appearance. These sludges also had different odors; the 31°C sludge had an earthy odor and the 41°C had a somewhat sweet odor.

Figure 29 shows the changes in settling characteristics that resulted from aerobic digestion at a temperature of 31°C. The settling characteristics of the sludge improved with treatment time up to a detention time of approximately seven days. The good settling characteristics at seven days indicated that solids recycle could be employed in the aerobic digestion process and thus possibly reduce the hydraulic detention time by approximately one half while retaining the same solids detention time.

Shown in Figure 30 are the COD, VSS, organic nitrogen and phosphate concentrations for the supernatant of an aerobically digested sludge that had been allowed to settle for one hour. The relatively low COD, VSS and organic nitrogen concentrations would impose an insignificant recycle load on a treatment plant. The phosphate concentration, however, could represent up to 25 percent of the influent concentration.

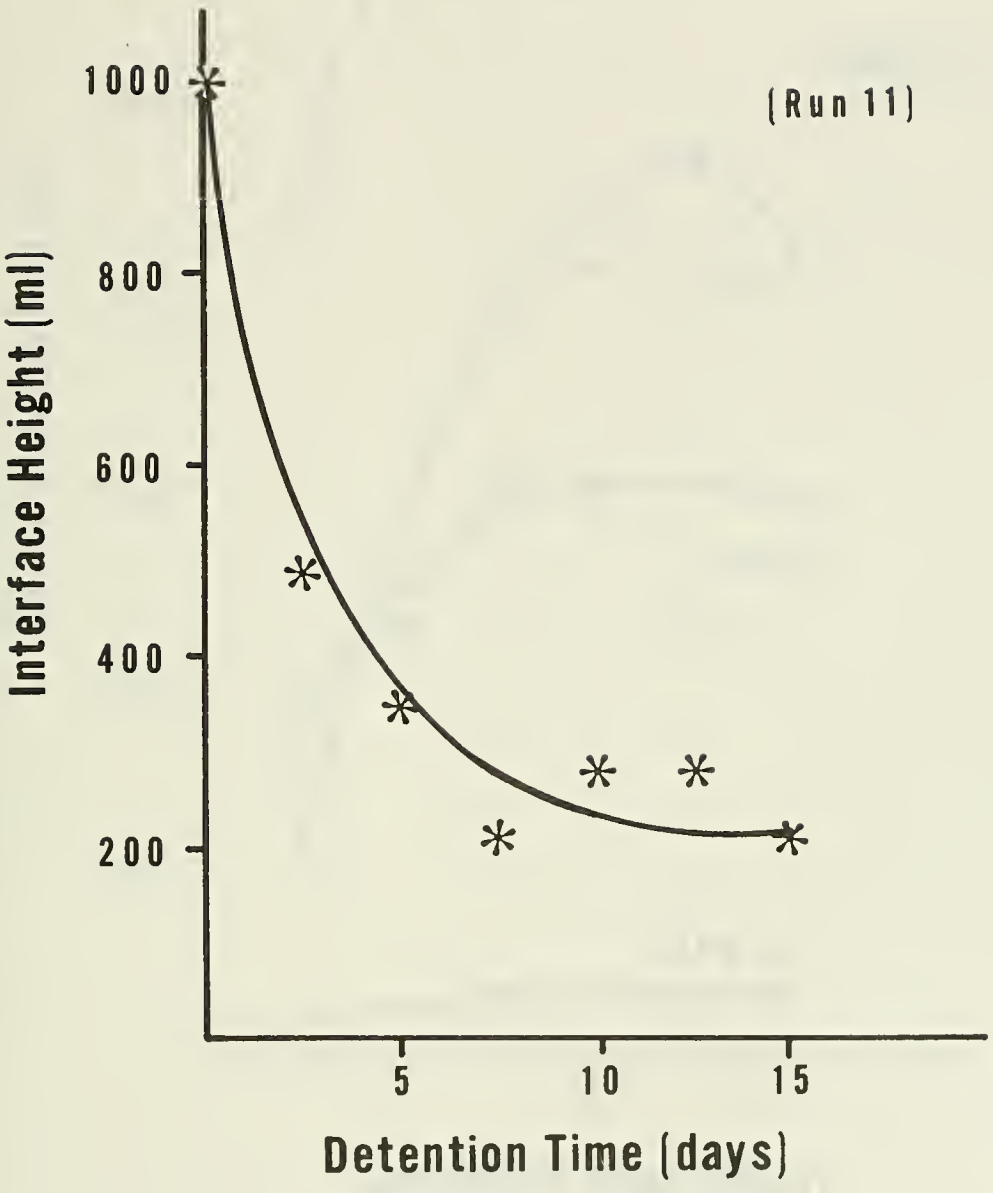

Figure 29

Variation of Settling Rate as a Function of Detention Time at 30°C

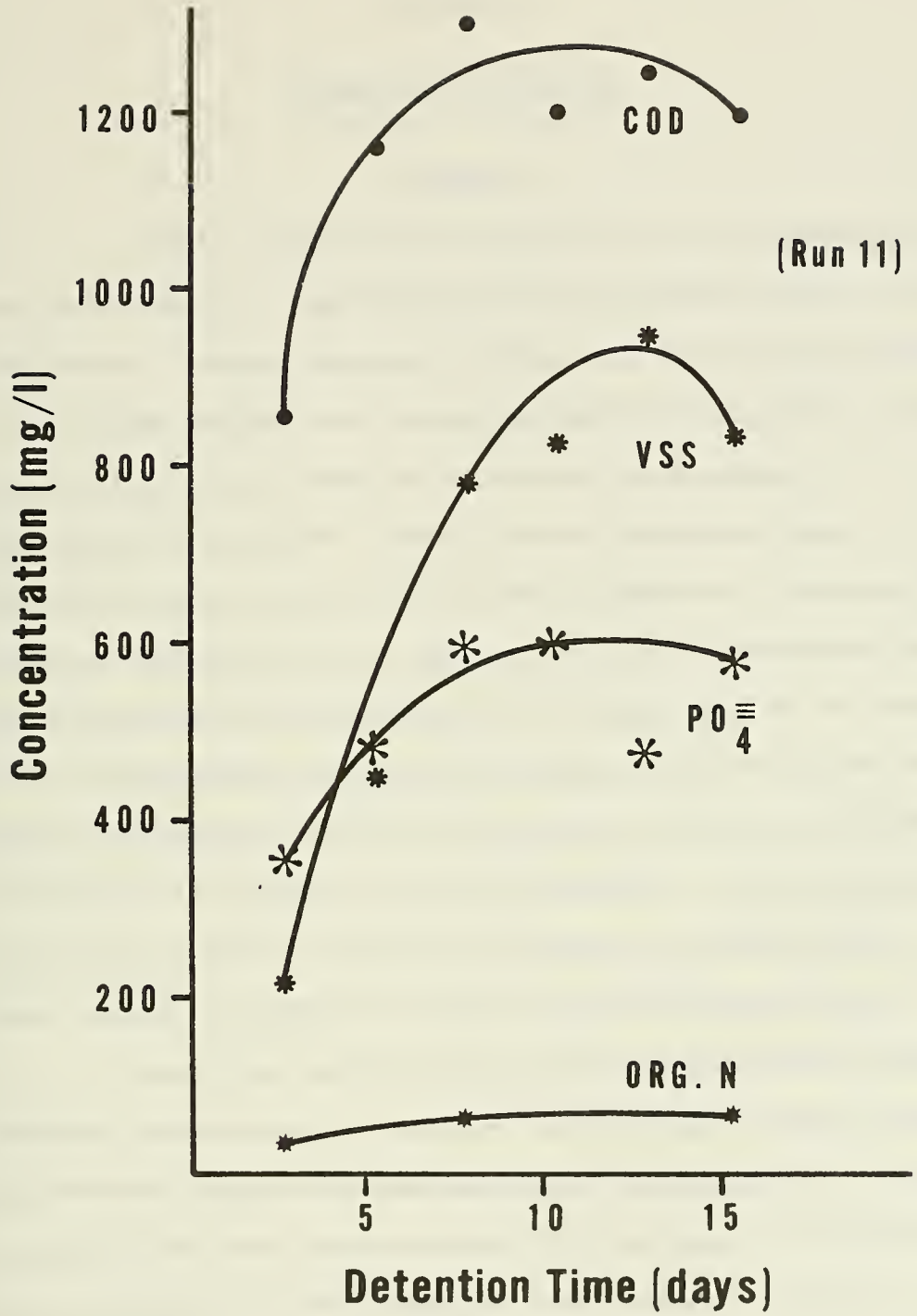

Figure 30

Supernatant Quality of Settled Aerobically Digested Sludge at 30°C

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

Aerobic digestion is governed by the microorganisms involved and their reaction to the various conditions imposed during process application. Aerobic digestion of waste activated sludge has traditionally been thought of as autometabolism of the bacterial cells previously developed during the activated sludge process. This concept has somewhat limited process application since bacteria utilize soluble substrates while digestion of waste activated sludge is concerned with the degradation of solid substrates. By controlling the solid concentration and temperature, it was found that other microorganisms, protozoa and rotifers, could be induced to grow. These microorganisms enhanced the process and caused an improvement of both the rate and extent of the VSS destruction. The microfauna utilized the bacteria and other solid debris as substrates and, through their internal processing, produced a very stable end product.

From pilot scale research it was found that the aerobic digestion process could be improved by operating at specific elevated temperatures below certain maximum solids concentrations. Two processes were found that were unique because of the optimum temperatures and solids levels discovered. These operating conditions were conducive to the development of specialized groups of microorganisms that produced the unique characteristics of both the process and product sludges. Two operating levels were found and two processes were defined, (1) a high

rate solids destruction process and (2) a complete sludge stabilization process.

Treatment temperatures ranging from 2° to 52°C were investigated. It was found that the high rate partial solids destruction process developed at 42° ± 4°C and that the complete stabilization process occupied at 30° ± 4°C. These temperature induced phenomena were found to be dependent upon solids concentration in that neither could be optimumly operated at feed sludge solids concentrations above approximately 2.5 percent TVS. In addition, both temperature induced processes were found to be dependent upon treatment time; the high rate process could be operated with only a three day detention time for maximum reduction and the complete stabilization process required a 12.5 day detention time to produce a stable sludge.

High Rate Biological Solids Destruction. The potential for operating a continuous high rate biological solids destruction process at 42° ± 4°C was discovered during batch testing. New protozoa populations were found to parallel sharp increases in the measured oxygen uptake rate. At 42°C, the initial protozoa population of the sludge would quickly disappear and after approximately three days of treatment, a new protozoa population appeared which was identified as Monadidae. Since the high oxygen uptake rate and new protozoa population lasted for only 24 to 48 hours under batch operation, the VSS and COD destructions were not significantly affected. The COD and VSS destructions were similar to those obtained by digesting at 30°C. When the 42°C process was operated on a continuous feed basis with a three day detention time, however, a 40 percent higher rate of volatile solids destruction was

obtained than at 30°C. The high rate process when fed a one percent sludge, maintained an oxygen uptake rate of 240 mg/hr/gVSS (100-125 mg/l/hr), a pH of 7.5, and alkalinity of 1500 mg/l. It required oxygen at the rate of 2.2 mg per mg of VSS destroyed. The product sludge settled to approximately 1.0 percent solids leaving a highly colored supernatant. This sludge was relatively unstable and developed septic characteristics within three days.

Complete Biological Stabilization. Operation of the aerobic digestion process at a temperature of 30°C $\pm$ 4°C with a feed solids concentration of less than 2.5 percent TVS produced the most stable sludges. This process was operated with a 12.5 day detention time and produced (1) a stable sludge that did not develop septic conditions within 60 days, (2) a sludge that would settle to approximately 2.5 percent solids within a 30 minute settling period leaving a high quality supernatant, (3) a highly nitrified sludge and (4) a sludge that would readily undergo biological denitrification if non-oxidative conditions were imposed. This process required oxygen at 9 mg/hr/gVSS and utilized 1.7 mg of oxygen per mg of VSS destroyed.

Production of a stable sludge involved the reduction of the energy content of the sludge to such a level that septic conditions, would not develop in the sludge during subsequent handling, treatment and disposal. This state was tested for by subjecting the samples to incubation at 37°C without aeration until septic conditions developed.

The high degree of stabilization produced at 30°C

resulted from the development of a succession of microorganisms. The environmental conditions that induced the growth of the protozoa, Aspidisca and Vorticella, Bdelloid, rotifers and the nitrifying bacteria, produced the most stable sludges. In the specified temperature and solids ranges the protozoa, Aspidisca and Vorticella proliferated and consumed large quantities of organic debirs. The Bdelloid rotifers further consumed large quantities of organic debris, protozoa and bacteria, and were most important in producing this desirable end product. These rotifers through their internal grinding and digesting of the solid debris contributed to the completion of the digestion process. At temperatures above 31°C, where these organisms did not develop, stabilization was impaired. At temperatures below 31°C where these organisms developed in lesser numbers, stabilization was slower.

It was found that solids concentration influenced not only the rate but also the extent of the reaction. Solids concentrations above 2.5 percent total volatile solids impaired the development of the free swimming protozoa and rotifers and, thus, impaired the process in that a longer treatment time was required to reach the same relative degree of stabilization.

In recycling of waste water sludges to the land, the controlling design criterion is often the amount of nitrogen in the sludge. The sludge application rate and therefore the amount of land required for recycling is directly related to the amount of nitrogen (ammonia, nitrite, nitrate and organic nitrogen), in the sludge to be applied. At 30°C and solids concentrations less than

2.5 percent, two inexpensive processes are available for removal of 50 to 60 percent of the initial sludge nitrogen. These processes are (1) biological denitrification or (2) elutriation.

Another major benefit of this process was the marked improvement in the settling characteristics of the product sludge. The sludge from this process was readily settled to 2.5 percent solids. The fact that this settling was effected without chemicals constitutes a major potential cost savings.

Conclusions

1. Both the rate and extent of the aerobic digestion reaction, as measured by the change in the sludge volatile solids, chemical oxygen demand or organic nitrogen, are dependent upon the sludge temperature. Optimum aerobic digestion operating conditions were found at temperatures of 30° $\pm$ 4°C and 42° $\pm$ 4°C.

2. Both the rate and extent of the aerobic digestion reaction, as measured by the change in the sludge volatile solids, chemical oxygen demand or organic nitrogen, are dependent upon the solids concentration of the sludge. Solids concentrations above 2.5 percent TVS were detrimental to the aerobic digestion process. The effect resulted from the change in the cludge community induced by the solids concentration.

3. Rate and extent of aerobic digestion were observed to be independent of the sludge dissolved oxygen concentration as long as it was obove 3 mg/1.

4. No significant process improvements were derived from oxygenation during aerobic digestion. Sludge solids concentrations for which oxygenation was required to maintain aerobic conditions were found to be detrimental to the optimum aerobic digestion process as noted above.

5. The ammonia generated from the decomposition of the organic nitrogen was rapidly nitrified. Nitrification most rapidly at a treatment of 30°C and an initial sludge solids concentration below 2.5 percent TVS.

6. Aerobic digestion is an alkalinity consuming reaction. Alkalinity is generated during organic nitrogen degradation, is consumed during nitrification, and can again be generated by denitrification. Approximately 1000 mg/l of additional alkalinity was required to maintain a favorable pH during nitrification of the available ammonia that resulted from the aerobic digestion of a one percent volatile solids sludge.

7. Under continuous feed conditions, the aerobic digestion reaction stabilized at a pH of approximately 4.7 when a one percent feed sludge was processed at 30°C for detention times longer than two days. Volatile solids reductions of 40 to 50 percent were obtained under these operating conditions. At a digestion temperature of 42°C $\pm$ 4°C, the digestion process stabilized at a pH of 7.8.

8. The microfauna populations developed during aerobic digestion were found to be decisive agents in the production of a stabilized sludge.

9. Significant populations of Bdelloid rotifers developed in the sludge at a digestion temperature of 30°C $\pm$ 4°C. On a batch basis, these microorganisms developed as the sludge approached a relatively stable condition. Sludges with significant rotifer populations had a relatively high degree of stability while those without these microorganisms were relatively unstable. Under optimum conditions, populations as high as 50,000 organisms per liter were developed.

10. The protozoa population of the waste activated sludge showed seasonal species variation which influenced the protozoa

population that developed during aerobic digestion. Changes in both the rate and extent of the volatile solids destruction obtained through aerobic digestion corresponded with these changes in protozoa.

11. An aerobic digestion temperature of 30° ± 4°C favored the early development of significant populations of protozoa identified as Vorticella and Aspidisca. The succession of microfauna at 30° ending with the Bdelloid rotifers produced the stable sludge.

12. An aerobic digestion temperature of 42° ± 4°C favored the development of a significant population of protozoa identifed as Monadidae. These highly active free swimming protozoa caused a high rate of volatile solids destruction. They were highly sensitive to sludge temperature and detention time, and developed only with a digestion temperature of 42° ± 4°C and within approximately three to five days of aerobic digestion. The limited number of microfauna at 42°C (only Monadidae) was detrimental to subsequent stabilization of the sludge.

13. An aerobic digester with a detention time of 12.5 days operated at a temperature of 30° ± 4°C, with a feed sludge solids concentration of less than 2.5 percent TVS, can produce a well stabilized sludge. This sludge can be stored without aeration at a temperature of 37°C, for as long as 60 days without the developement of septic conditions.

14. A well stabilized sludge can be produced with a variety of aerobic digester operating conditions; however, the stabilization is optimumized at 30° ± 4°C and a initial sludge solids concentration below 2.5 percent TVS.

15. The settling characteristics of the sludge were found to be dependent upon the conditions under which the digestion process was operated. The most easily separated sludges were produced with a digester temperature of 30° ± 4°C and a feed sludge solids concentration less than 2.5 percent TVS.

16. A high rate aerobic digestion process for waste activated sludge has been discovered involving the incorporation of specific temperature, detention time, solids and dissolved oxygen levels in process operation. The process produced optimum solids destruction that cannot be obtained without the specific temperature of 42° ± 4°C and a feed sludge solids concentration of less than approximately 2.5 percent. This process is particularly attrative for using in existing plant operating beyond their sludge handling design capacity. The installing temperature and solids control equipment the solids destruction capability of plants could be increased 40 to 60 percent. The process is capable of destroying 47 percent of the volatile suspended solids with a three day detention time.

17. An aerobic digestion process that produces a stabilized sludge has been discovered involving the incorporation of specific temperature, solids, and dissolved oxygen levels. This process is also unique in that it produces highly desirable optimum results that cannot be obtained without the specific temperature of 30° ± 4°C and solids concentrations of less than 2.5 percent total volatile solids. A well stabilized sludge can be produced with a process detention time of 12.5 days. This process is particularly attractive when land disposal is contemplated since it produces a humus material containing two to three percent solids. The product sludge is highly

ameanable to biological dentrification.

CHAPTER VII

RECOMMENDATIONS

1. A detailed laboratory investigation should be undertaken to confirm these findings for other types and mixtures of sludges.

2. Pilot scale aerobic digestion studies of waste activated sludge should be undertaken that include temperature and solids control. Separate studies should be done focusing on each of the processes, the sludge solids destruction process and the sludge stabilization process.

3. Studies should be undertaken that include a broader range of combinations of the various operating parameters.

4. A more detailed study of the sludge ecosystem should be conducted.

5. Land application of the stabilized sludge should be studied to confirm the stability test results and the effects that this method of sludge disposal would have on the environment.

6. Various means of thickening the aerobically digested sludges should be studied to determine the most economical solution to this sludge handling problem.

7. Because of the shortages of nitrogen compounds for commercial fertilizers, the value of aerobically digested sludge as a source of nitrogen should be evaluated.

8. The fate of pathogenic organisms in the aerobic digestion process should be determined, especially for consideration of land application.

9. Virial studies should be conducted.

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APPENDIX A

SUMMARY OF EXPERIMENTS

RUN	EXPERIMENT	TEMP. °C	D.O. mg/l	INITIAL TVS.%	COMMENT
0	0-A	2	3-7	0-6	Batch Air
	0-B	13	3-7	0.6	" "
	0-C	24	1-5	0.6	" "
	0-D	31	2-5	0.6	" "
	0-E	42	2-5	0.6	" "
	0-O	26	10-15	0.6	Batch, O_2
1	1-1	25	17	0.45	Batch, O_2
	1-2	25	3	1.30	" "
	1-3	25	7	1.30	" "
	1-4	25	14	1.30	" "
	1-5	25	14	1.70	" "
	1-6	25	10	2.20	" "
2	2-1	26	19	2.30	Batch, O_2
	2-2	26	20	1.00	" "
	2-3	26	17	1.10	" "
	2-4	26	12	3.50	" "
	2-5	25	16	0.43	" "
	2-6	25	16	0.43	" "

RUN	EXPERIMENT	TEMP. °C	D.O. mg/l	INITIAL TVS.%	COMMENT
3	3-1	25	10	3.40	Batch, O_2
	3-2	25	3	3.30	" "
	3-4	25	<1	3.30	" "
	3-5	25	10	3.30	" "
4	4-1	25	25	2.80	Batch, O_2
	4-2	25	15	3.00	" "
	4-3	25	<1	2.90	" "
	4-4	52	40	3.00	" "
	4-5	52	40	2.80	" "
5	5-2	37	10	2.60	Batch, O_2
	5-3	31	10	2.60	" "
	5-4	42	20	1.00	" "
	5-5	42	15	2.10	" "
	5-6	42	15	2.5	" "
6	6-2	31	4	0.84	Batch, Air
	6-3	31	17	0.84	Batch, O_2
	6-4	41	2	0.79	Batch, Air
	6-5	41	15	0.76	Batch, O_2

RUN	EXPERIMENT	TEMP.°C	D.O. mg/l	INITIAL TVS.%	COMMENT
7	7-1	26	15	0.76	Batch, O_2
	7-2	29	5	0.74	Batch Air
	7-3	50	15	0.75	Batch, O_2
	7-4	40	17	0.72	Batch, "
	7-5	41	20	0.83	" "
	7-6	50	3	0.72	Batch Air
8	8-1	30	3	0.87	Batch Air
	8-2	40	4	0.83	" "
	8-3	40	5	0.85	" "
	8-4	30	3	0.83	" "
	8-5	30	3	0.82	" "
	8-6	30	3	0.85	" "
9	9-1	30	10	2.6	Batch, O_2/Air
	9-2	30	10	0.8	" "
	9-3	30	10	1.2	" "
	9-4	30	5	0.4	Batch Air

RUN	EXPERIMENT	TEMP.°C	D.O. mg/l	INITIAL VS.%	COMMENT
					Continuous Detention Time, days
10	10-2	42	2	0.9	3
	10-4	30	6	0.5 (10-2)	10 (13 day)
	10-5	30	6	0.4 (10-7)	10 (15 day)
	10-6	30	4	0.9	6-2/3
	10-7 (10 liter)	27	10	0.9	5
	10-8 (10 liter)	27	2	0.9	10
					Continuous Detention Time, days
11	11-1	30	2	0.9	2-1/2
	11-2	30	4	-	5
	11-3	30	5	-	7-1/2
	11-4	30	7	-	10
	11-5	30	7	-	12-1/2
	11-6	30	7	-	15
	11-7 (10 liter)	27	10	0.9	5
	11-8 (10 liter)	27	2	0.9	10

APPENDIX B

TIME FOR SEPTIC CONDITIONS, DAYS

DIGESTION TREATMENT TIME, DAYS	EXPERIMENTAL CONDITIONS	Digester 5-2	5-3	5-4	5-5	5-6
6		3	4	5	4	4
9		12	9	11	9	10
17		12	12	26	9	9
43		23	23	23	20	20
		Digester 6-2	6-3	6-4	6-5	
10		13	14	14	10	
15		23	23	17	17	
		Digester 7-1	7-2	7-3	7-4	7-5	7-6
8		6	6	10	7	7	7
14		10	30	10	12	12	12
24		19	19	19	12	12	-
		Digester 8-1	8-2	8-3	8-4	8-5	8-5
7		2.7	3	21	5	41	60
12		12	11	12	9	14	9
14		12	12	9	16	12	12

APPENDIX B (CONT.)

TIME FOR SEPTIC CONDITIONS, DAYS					
DIGESTION TREATMENT TIME, DAYS	EXPERIMENT CONDITIONS	Digester			
		9-1	9-2	9-3	9-4
7		6	4	4	4
10		6	5	5	5
13		6	6	6	34
15		11	13	11	34
22		30	35	35	35

APPENDIX C
ANALYSIS OF STABILITY SAMPLES

AEROBIC DIGESTION TIME, DAYS	STABILITY TEST DAYS	COD mg/1	NH_3 mg/1	NITROGEN ORG mg/1	NITROGEN NO_3^-	PH	RESP. RATE mg/hr/gVSS	STATE
RUN #5 4/9	5-10 4/9							
15	20	3600 3400	100 173	300 148	200 0	4.8	5.1	STABLE 37 DAYS
#6 4/9	6-10 4/9							
6-2/3	20	7600 5800	80 228	380 241	300 25	4.7 7.1	8.6	ANAEROBIC 8 DAYS
#5 4/13	5-10 4/13							
15	16	4490 4000	113 181	292 167	200 40	4.5 7.4	4.1	ANAEROBIC 27 DAYS
#6 4/13	6-10 4/13							
6-2/3		7500 5500	93 244	365 203	300 25	5.0 7.5	10.2	ANAEROBIC 6 DAYS
#5 4/20	5-10 4/20							
15	9	5400 4800	120	230	290 62.5	4.5 7.3	2.48	ANAEROBIC 26 DAYS

APPENDIX C (CONT.)

DIGESTION TIME, DAYS	STABILITY TEST DAYS	COD mg/1	N43 mg/1	NITROGEN ORG mg/1	NITROGEN mg/1	PH	RESP. RATE mg/or/g VSS	STATE
#4 40°-30° 4/20	4-10 4/20							
13	9	6100 6012	180	330	80 100	6.2 7.3	2.48	STABLE 20 DAYS
#2 40° 4/20	2-10 4/20							
3	9	7500 7500	300 464	440 321	30 0	7.7 7.5	21	ANAEROBIC 3 DAYS
#8 4/20	8-10 4/20							
10	16	5800 5100	132	296	300 25	5.3 7.55	13.5	ANAEROBIC 6 DAYS

APPENDIX D

VSS, PERCENT REMAINING

RUN 0

Time, hr	DIGESTION TEMPERATURE					
	2°C (OA)	13°C (OB)	24°C (OC)	31°C (OD)	42°C (OE)	26°C (OO)
0	100	100	100	100	100	100
9	100	95	100	93	78	87
24	100	92	85	82	68	75
57	95	85	77	72	65	68
78	95	82	70	67	60	60
102	93	78	63	62	55	53
150	92	74	58	60	49	53
194	89	70	53	58	43	53
270	87	67	53	57	40	52
364	82	63	52	42	27	--
732	67	42	33	27	25	--

APPENDIX E

COD, PERCENT REMAINING

RUN 0

Time, hr	DIGESTION TEMPERATURE					
	2°C (OA)	13°C (OB)	24°C (OC)	31°C (OD)	42°C (OE)	26°C (OO)
0	100	100	100	100	100	100
9	91	85	90	85	91	75
24	89	85	71	82	82	65
57	91	79	70	63	71	61
78	95	76	70	58	67	54
102	88	70	62	58	57	54
150	84	69	53	57	52	50
194	88	65	55	53	48	50
270	68	56	49	46	34	46
364	79	59	47	35	27	--
732	68	43	33	28	25	--
1044	59	38	--	--	--	--

APPENDIX F

RUN ZERO EXPERIMENTAL DATA

June 4, 1972

$2^{o}C$ (OA)

$13^{o}C$ (OB)

$24^{o}C$ (OC)

$31^{o}C$ (OD)

$42^{o}C$ (OE)

$26^{o}C$ (OO)

Reactor	Time, hr	TVS mg/l	VSS mg/l	VS_D mg/l	COD mg/l	COD_D mg/l	ph mg/l	ALK mg/l	SET ml
OA	0	6200	6000	200	10500	46	7.5		20
	9	6400	6200	200	9600				
	24	6000	6000	0	9300				20
	57	5900	5700	200	9600				20
	78	5600	--	--	10000				
	102	5900	5600	300	9200		8.3		5
	150	4700	--	--	8800				20
	194	5300	5300	0	9200	126			
	270	5000	5200	0	7100		8.2		10
	364	4800	4900	0	8300				10
	732	4100	4000	0	7100	178	8.35	723	15
	1044			0	6200				
OB	0	6200	6000	200	10500	46	7.5		70
	9	6100	5700	400	8900				
	24	5800	5500	300	8900				100
	57	5400	5100	300	8300				40
	78	5200	--	--	8000				
	102	5000	4700	300	7400		8.4		10
	150	4100	--	--	7200				10
	194	4000	4200	200	6800	134			
	270	4000	4000	0	5900		8.4		20
	364	3700	3800	0	6200				10
	732	2900	2500	400	4500	284	6.4	231	50
	1044				4000				

Reactor Time, hr		TVS mg/l	VSS mg/l	VS_D mg/l	COD mg/l	COD_D mg/l	ph mg/l	ALK mg/l	SET ml
OC	0	6200	6000	200	10500	46	7.3		90
	9	6100	6100	0	9400				
	24	5300	5100	200	7500				90
	57	4700	4600	100	7400				40
	78	4500	--	--	7400				
	102	4100	3800	300	6500		7.7		100
	150	3200	--	--	5600				100
	194	3400	3200	200	5800	289			
	270	3300	3300	0	5100		6.4		30
	364	3200	3100	100	4900				20
	732	2400	2000	400	3500	154	4.7	22	575
	996		1800				4.85	26	
OD	0	6200	6000	200	10500	46	7.8		140
	9	5400	5600	0	8900				
	24	5300	4900	400	8600				80
	57	4300	4300	0	6600				160
	78	4300	--	--	6100				
	102	4100	3700	400	6100		6.3		250
	150	3800	--	--	6000				210
	194	3600	3500	100	5600	210			
	270	3700	3400	300	4800		5.6		400
	364	2600	2500	100	3700				770
	732	2000	1600	400	2900		4.7	28	850
	1044						5	38	

Reactor Time, hr		TVS mg/l	VSS mg/l	VS_D mg/l	COD mg/l	COD_D mg/l	ph mg/l	ALK mg/l	SET ml
OE	0	6200	6000	200	10500	46	7.2		300
	9	5600	4700	900	9600				
	24	4800	4100	700	8600				250
	57	4600	3900	700	7400				310
	78	4500	--	--	7000				
	102	4000	3300	700	6000		8.4		400
	150	3400	--	--	5500				420
	194	3200	2600	600	5000	673			
	270	2500	2400	100	3600		8.0		600
	364	1700	1600	100	2800				700
	732	1800	1500	300	2600	154	6.1	250	750
	1044						6.6	1365	
OO	0	6200	6000	200	10500	46	7.2		0
	9	5300	5200	100	7900				
	24	4900	4500	400	6800				100
	57	4200	4100	100	6400				100
	78	3900	--	--	5700				
	102	3700	3200	500	5700		6.25		40
	150	3300	--	--	5200				100
	194	3300	3200	100	5200	297			
	270	3200	3100	100	4800				
	364	--	--	--	--				
	732	--	--	--	--				
	1044	--	--	--	--				

APPENDIX G

RUN 5 EXPERIMENTAL DATA

October 23, 1972

OXYGEN UPTAKE, mg/l/hr

Time, hr	37°C (5-2)	31°C (5-3)	42°C (5-4)	42°C (5-5)	42°C (5-6)
0	595	621	137	405	414
5	585	378	211	288	432
18	207	261	81	180	360
55	-	104	-	103	65
72	51	83	81	61	173
138	225	77	36	70	41
174	43	61	9	24	34
217	29	-	8	14	18
241	30	36	7	14	-
437	18	15	8	6	-
560	8	-	6	6	16

Digester 5-2

Reactor Time, hr	TVS mg/1X10^{-3}	VSS mg/1X10^{-3}	VS_D mg/1	COD mg/1X10^{-3}	COD_D mg/1X10^{-3}	pH
5-2 0	26.2	23.2	3000	38.0	0.66	6.8
37°C 9½	24.5	21.4	3100	35.5	--	--
24	22.7	19.9	2800	33.5	1.06	7.6
72	20.4	18.1	2300	30.0	--	7.25 6.70
138	18.0	15.5	2500	23.9	0.91	7.3
174½	16.3	13.9	2400	22.0	--	7.6
217	14.9	12.9	2000	21.7	0.72	7.1
264½	14.1	12.0	2100	20.2	--	7.15 6.38
336½	13.6	12.0	1600	19.7	--	6.40
408	14.0	11.9	2100	19.2	1.31	6.5
480	13.6	11.7	1900	19.2	--	6.5
552	13.6	11.1	2500	20.1	1.97	6.75
1080	11.9	9.25		15.0	1.63	

Digester 5-3

Reactor Time, hr	TVS mg/1X10^{-3}	VSS mg/1X10^{-3}	VS_D mg/1	COD mg/1X10^{-3}	COD_D mg/1X10^{-3}	pH
5-3 0	25.9	24.1	1800	37.5	--	6.8
31°C 9½	25.5	22.9	2600	35.3	--	--
24	24.4	21.4	3000	34.7	0.44	7.4
72	22.0	19.9	2100	32.2	--	6.8 6.7
138	20.3	17.4	2900	26.0	0.66	6.5
174½	19.8	16.8	3000	26.3	--	6.3
217	18.4	15.4	3000	24.9	1.11	6.10
264½	17.8	14.3	3500	23.8	--	6.00 6.12
336½	17.8	14.3	3500	22.8	--	6.15
408	17.3	13.7	3600	19.7	0.46	5.7
480	17.0	13.5	3500	20.5	--	5.3
552	16.0	12.7	3300	20.9	0.63	5.0
1080	14.6	10.9		15.5	0.8	

Digester 5-4

Reactor Time, hr	TVS mg/1X10^{-3}	VSS mg/1X10^{-3}	VS_D mg/1	COD mg/1X10^{-3}	COD_D mg/1X10^{-3}	pH
5-4 0	10.6	10.3	300	15.0	0.30	6.9
42°c 9½	9.23	8.45	780	12.7	--	--
24	8.98	8.20	780	13.0	0.82	6.6
72	8.02	7.20	820	11.6	--	7.45 7.45
138	6.65	5.90	750	8.27	0.67	7.65
174	6.34	5.70	640	8.60	--	7.90
217	6.42	5.50	920	8.48	0.84	7.92
264½	6.30	5.30	1000	8.66	--	8.00 8.20
336½	6.14	5.30	840	8.07	--	8.32
408	6.06	5.00	1060	7.20	1.07	8.4
480	5.95	4.80	1150	7.70	--	8.4
552	5.95	4.80	1150	7.57	1.67	8.4
1080	5.59	4.11		6.80	1.5	

Digester 5-5

Reactor Time, hr	TVS mg/1X10^{-3}	VSS mg/1X10^{-3}	VS_D mg/1	COD mg/1X10^{-3}	COD_D mg/1X10^{-3}	pH
5-5 0	20.9	19.8	1100	29.3	0.44	6.8
42°C 9½	19.4	16.9	2500	29.2	--	--
24	17.3	14.8	2500	24.5	1.86	7.6
72	15.4	13.2	2200	22.3	--	6.75 7.30
138	12.9	10.8	2100	16.0	1.40	7.70
174½	12.4	10.5	1900	17.2	--	7.89
217	11.8	10.2	1600	15.6	1.63	8.00
264½	12.0	9.7	2300	16.9	--	8.05 8.15
336½	11.6	9.70	1900	13.6	-	8.38
408	12.1	9.50	2600	15.5	2.23	8.30
480	11.3	9.50	1800	15.5	--	8.25
552	11.3	8.66	2640	15.9	3.14	8.2
1080	11.0	8.45		14.4	2.45	

Digester 5-6

Reactor Time, hr	TVS mg/1X10^{-3}	VSS mg/1X10^{-3}	VS_D mg/1	COD mg/1X10^{-3}	COD_D mg/1X10^{-3}	pH
5-6 0	24.8	22.7	2100	33.0	0.44	6.90
42°C 9½	23.4	20.2	3200	33.0	--	--
24	21.7	18.8	2900	32.0	1.74	7.50
72	19.3	17.1	2200	27.8	--	7.30 7.30
138	16.2	13.7	2500	20.5	1.66	7.60
174½	15.6	13.0	2600	21.3	--	7.79
217	15.2	12.6	2600	21.1	1.95	8.1
264½	15.1	12.0	3100	21.7	--	8.15 8.22
336½	15.0	11.9	3100	19.5	--	8.48
408	15.1	11.8	3300	19.7	2.41	8.4
480	13.9	11.6	2300	19.6	--	8.45
552	13.9	11.3	2600	19.9	3.40	8.42
1080	12.8	9.1		16.6	3.13	

SOLIDS DATA
Digester 5-2

Time, hr		TS	TVS	TFS	TSS	VSS	VSD	TDS
5-2	0	32,100	26,200	5,900	28,200	23,200	3,000	3,900
	9½	30,500	24,500	6,000	26,300	21,400	3,100	4,200
	24	28,500	22,700	5,800	24,700	19,900	2,800	3,800
	72	25,900	20,400	5,500	22,700	18,100	2,300	3,200
	138	23,500	18,000	5,500	19,700	15,500	2,500	3,800
	174	21,700	16,200	5,500	18,500	13,900	2,300	3,200
	217	20,100	14,800	5,200	17,000	12,900	1,900	3,100
	264	19,600	14,100	5,500	16,100	12,000	2,100	3,500
	336	19,000	13,600	5,400	16,200	12,200	1,400	2,800
	408	19,300	14,000	5,300	15,800	11,900	2,100	3,500
	480	19,100	13,600	5,500	15,700	11,700	1,900	3,400
	552	19,000	13,600	5,400	15,100	11,100	2,500	3,900
	1080	17,400	11,900	5,500	13,600	9,250	2,650	3,800

SOLIDS DATA
Digester 5-3

Time, hr	TS	TVS	TFS	TSS	VSS	VSD	TDS
5-3 0	32,000	25,900	6,100	28,900	24,100	1,800	3,100
9½	31,600	25,500	6,100	28,000	22,900	2,600	3,600
24	30,500	24,400	6,100	26,700	21,400	3,000	3,800
72	27,800	22,000	5,800	24,400	19,800	2,200	3,400
138	25,900	20,300	5,600	22,000	17,400	2,900	3,900
174	25,700	19,800	5,900	21,200	16,800	2,000	4,500
217	24,100	18,400	5,700	19,600	15,400	3,000	4,500
264	23,500	17,800	5,700	18,400	14,300	3,500	5,100
336	23,600	17,800	5,800	18,900	14,800	3,000	4,700
408	23,000	17,300	5,700	17,800	13,700	3,600	5,200
480	21,700	16,000	5,700	17,500	13,500	2,500	4,200
552	22,800	17,000	5,800	16,300	12,700	4,300	6,500
1080	20,500	14,700	5,800	14,500	10,900	3,800	6,000

SOLIDS DATA
Digester 5-4

Time, hr		TS	TVS	TFS	TSS	VSS	VSD	TDS
5-4	0	12,900	10,600	2,300	12,500	10,300	300	400
	9½	11,400	9,230	2,270	10,200	8,500	730	1,200
	24	11,200	8,980	2,120	9,800	8,200	780	1,400
	72	10,300	8,020	2,280	9,020	7,370	650	1,280
	138	8,800	6,660	2,140	7,510	5,920	740	1,290
	174	8,510	6,340	2,170	7,310	5,650	690	1,200
	217	8,630	6,420	2,210	7,050	5,490	930	1,580
	264	8,540	6,300	2,240	6,870	5,280	1,020	1,670
	336	8,390	6,140	2,250	7,070	5,380	760	1,320
	408	8,380	6,060	2,232	6,700	5,010	1,050	1,680
	480	8,280	6,000	2,280	6,080	4,880	1,120	2,200
	552	8,260	5,950	2,310	6,470	4,900	1,050	1,790
	1080	7,950	5,600	2,350	5,720	4,120	1,480	2,230

SOLIDS DATA, Digester 5-5

Time, hr	TS	TVS	TFS	TSS	VSS	VSD
5-5 0	25,600	20,900	4700	23,900	19,800	4100
9½	23,900	19,400	4500	20,600	16,900	3700
24	21,500	17,300	4200	18,500	14,900	3600
72	19,500	15,400	4100	16,500	13,200	3300
138	17,100	12,900	4200	14,300	10,800	3500
174	16,600	12,400	4100	13,800	10,500	3300
217	15,900	11,800	4100	13,200	10,200	3000
264	16,100	12,000	4100	12,900	9,650	3250
336	15,800	11,600	4200	12,900	9,680	3220
408	16,400	12,100	4300	12,800	9,500	3300
480	15,900	11,700	4200	12,900	9,470	3430
552	15,600	11,300	4300	11,700	8,590	3110
1080	15,400	11,000	4400	11,700	8,330	3270

SOLIDS DATA, Digester 5-6

Time, hr		TS	TVS	TFS	TSS	VSS	VSD
5-6	0	30,300	24,800	5500	27,400	22,700	4700
	9½	28,900	23,400	5500	24,700	20,200	4500
	24	27,200	21,700	5500	23,500	18,800	4700
	72	24,700	19,300	5400	21,600	17,100	4500
	138	21,500	16,200	5300	18,200	13,700	4500
	174	21,100	15,600	5500	17,500	13,000	4500
	217	20,500	15,200	5300	16,800	12,600	4200
	264	20,600	15,100	5500	16,000	11,700	4300
	336	20,600	15,000	5600	16,700	12,300	4400
	408	20,700	15,100	5600	16,500	11,900	4600
	480	20,000	14,600	5400	16,200	11,600	4600
	552	19,400	13,960	5440	16,000	11,400	4600
	1080	18,400	12,900	5500	13,200	9,050	4150

APPENDIX H

EXPERIMENTAL DATA, RUN 6

Digester 6-2

Time,hr	TS mg/l	TSS mg/l	VSS mg/l	COD mg/l	pH	ALK mg/l	D.O. mg/l	SETTLING ml	PROTOZOA #OBS*
0	10,700	9,860	8,120	14,400	7.20		0.5	998	0
1					7.15		1.8	900	
3					7.40	542	3.0	980	
17					7.20		3.8	900	1
23	8,950	8,160	6,700	10,900		477			
27							3.8	800	1
41					7.00		0.3(F)	800	8(SV)
48							2.0	770	9
63							2.4	600	2
72	7,530	6,580	4,980	8,140	7.25	827			
78							2.4	570	
91							3.2	500	3(SV)
102					7.35		2.6	500	2

Digester 6-2 (Cont.)

Time,hr	TS mg/l	TSS mg/l	VSS mg/l	COD mg/l	pH	ALK mg/l	D.O. mg/l	SETTLING ml	PROTOZOA #OBS*
114							3.3	550	2
120	6,100	5,105	3,750	5,760	6.40	481	5.3	550	2(R)
139					6.30		5.3	560	1(R)
148							5.0	530	
159									2(R)
168	6,060	4,840	3,610	5,725	6.40	510	4.4	470	2(A,R)
196					6.30	438		470	2
240	6,190	4,460	3,340	5,370	6.25	346		420	1(R)
360	5,280	3,615	2,655		5.10	68			

SV - SESSILE VORTICELLA
R - ROTIFER
A - AMOEBA

Digester 6-3

Time,hr	TS mg/l	TSS mg/l	VSS mg/l	COD mg/l	pH	ALK mg/l	D.O. mg/l	SETTLING ml	PROTOZOA #OBS*
0	10,800	10,000	8,400	14,300	7.10		30	998	0
1					6.70		15	1000	
3					6.90	587		940	
17					7.05		26	910	0
23	9,800	9,110	7,250	12,200		518			
27								790	2
41							17	610	27(V)
48					6.80		25	650	17(V)
63					7.00		21	480	27(P)
72	8,170	7,190	5,640	9,050		948			
78							22	490	
91							22	500	8(SV)
102					7.40		22	450	29SV)
114							25	450	6(SV)
120	6,890	5,180	4,260	6,430	7.46	1650	22	410	6(SV)

Digester 6-3 (Cont.)

Time,hr	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
139					7.50		20	360	6(SV)
148							21	390	
159									3
168	6,230	5,130	3,580	5,820	7.78	1920	21	400	3
196					7.80	1824		390	1
240	6,010	4,880	3,290	5,750	7.48	1292		370	1
360	5,620	4,530	3,090		6.60	623			

*V - VOTICELLA
P - PARAMECIUM
SV - SESSILE VORTICELLA

Digester 6-4

Time,hr	TS	TSS	VSS	COD	pH	ALK	D.O.	SETTLING	PROTOZOA
Ø									
0	10,100	9,360	7,780	13,700	7.3		3.1	910	0
1					7.2		0.9	950	
3					7.2	497	0.3	900	
17					7.3		0.7	970	0
23	9,080	8,100	6,350	11,100		618			
27							0.5	980	0
41					7.2		2.1	670	0
48							3.0	620	0
63					7.1		0.3	850	20(M)
72	7,780	6,730	5,180	8,620		899			
78							0.3	610	
91							0.3	650	43(M)
102					7.8		2.5	550	29(M)
114							3.4	590	7(M)

Digester 6-4 (Cont.)

Time,hr	TS	TSS	VSS	COD	pH	ALK	D.O.	SETTLING	PROTOZOA
120	6,260	4,850	3,410	5,420	8.2	1847	3.6	560	1(M)
139								570	1(M)
148					8.1		1.4	580	
159									
168	5,890	4,500	3,050	5,300	8.4	1870	1.5	470	0
196					8.5	1793		500	0
240	5,750	4,330	2,840	5,130	8.6	1680		400	0
360	5,586	4,320	2,725		8.7	1566			

Digester 6-5

Time,hr	TS	TSS	VSS	COD	pH	ALK	D.O.	SETTLING	PROTOZOA
0	9,790	9,110	7,520	13,100	7.1		30	900	0
1					6.8		17	890	
3					6.9	555	13	890	
17					7.3		20	900	0
23	8,700	7,600	6,190	10,500		555	(F)		
27							0.4(F)	790	0
41					6.8		18	400	0
48							20	420	0
63					7.1		20	350	2(M)
72	7,730	6,360	5,020	8,570		747			
78								450	
91							14	400	23(M)
102					7.5		16	500	38(M)
114					7.9		20	520	3(M)
120	5,770	4,290	3,080	5,080		1748		490	2(M)

Digester 6-5 (Cont.)

Time,hr	TS	TSS	VSS	COD	pH	ALK	D.O.	SETTLING	PROTOZOA
139								500	0
148					7.8		18	500	
159									0
168	5,460	4,030	2,680	4,860	8.1	1690	20	470	
196					8.2	1687		500	0
240	5,420	4,100	2,680	4,900	8.2	1654		430	0
360		3,670	2,460		8.8	1577			

OXYGEN UPTAKE RUN 6
mg/l/hr

Time, hr	6-2	6-3	6-4	6-5
0	200	213	215	168
5	90	107	212	250
10	41	49	130	94
27	72	66	107	180
41	125	122	84	89
48	90	97	63	54
63	87	97	108	86
76	75	87	208	118
90	65	70	168	186
102	65	60	98	130
114	65	54	46	41
126	9.0	45	31	20
142	13	26	9	26
195	9.0	26	26	22
243	11	15	6	16

APPENDIX I
EXPERIMENTAL DATA
RUN 7-1

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
0	15	9620	7590	2030	8790	7290	300	11,800
4								
9								
20								
25		8900	6910	1990	8010	6700	210	9600
31								
45								
72		7070	5040	2030	5780	4600	440	7200
76								
92								
100								
120		6340	4270	2070	4950	3710	560	5800
129								
144								
151								

RUN 7-1

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
168								
171								
190								
194	350	5850	3770	2080	4680	3430	340	5400
216								
240	276	5850	3770	2080	4680	3360	410	5180
320	86	5850	3730	2120	4260	3050	680	5160
332								
368								
384								
392								
432	86.9	5984	3814	2170	4230	3050	764	4762
464	94.4							
512	85							
576	72	5950	3200	2750	4140	2930	270	5135
600								

RUN 7-1

Time	COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE mg/l/hr	pH	ALK	D.O.	SET	PROTOZOA
0	165			78	6.95	600	20	990	-
4					6.75		25	970	1
9				65					2
20				50	6.85		20	980	3
25	306				7.00	500		990	
31				73				990	16
45				89	6.91		20	800	32
72	578	1058	605	68	7.32		15	450	7
76								450	
92				50	7.65		18	600	3
100								600	
120		845	560	17.5			25	600	1
129								690	
144				4	7.76	1740	15	710	1
151								670	
168					7.71			700	1

RUN 7-1

Time	COD_D	SUPERNATANT COD	SUPERNATANT NH_3	SUPERNATANT VSS	O_2 UPTAKE mg/1/hr	pH	ALK	D.O.	SET	PROTOZOA
171									680	
190									680	
194	331	688		360	24.4	7.46	1530	10		
216										1
240						7.0	916		620	
320	571	1200		310	NMO	6.4	524		700	
332									800	
368						6.5	533		700	
384							533		670	
392							520		750	
432			86.4	610	NMO	6.61	569		800	
464						6.7/7.5	590/1181		750	
512					2.16	7.85	1112		600	
576	519	1260							500	
600										

EXPERIMENTAL DATA

RUN 7-2

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
0	15	9530	7440	1990	8770	7160	280	12,200
4								
9								
20								
25		8210	6290	1920	7420	6130	160	8500
31								
45								
72		6680	4720	1950	5640	4420	300	6600
76								
92								
100								
120	100	6020	4080	1940	4760	3740	340	5770
129								
144								
151								

EXPERIMENTAL DATA

RUN 7-2

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
151								
168								
171								
190								
194	135	5890	3940	1950	4250	3230	710	5150
216								
240	127	5950	4050	1950	3900	2940	1110	4700
320	54	5880	3900	1980	3640	2710	1200	4270
332								
368	56							
384		6190	4100	2090	3470	2550	1559	3870
385								
392	59							
432	33	6580	3920	1660	3560	2540	1382	4170
464	30							
512	6.16							
600								

EXPERIMENTAL DATA (Cont.)
RUN 7-2

Time	SUPERNATANT COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
0	157		310	90	6.95	600		990	
4							2.5	970	1
9				76.5	7.35		4.0		+1
20				106	7.10		4.0	800	5
25	314	312	175		7.19	530		800	
31				118			0.6	800	41
45				81	7.50		1.4	790	11
72	341	483	445	61	7.62		2.9	500	4
76									
92				25.2	6.50		6.4	800	1
100								900	
120		775	435	6.3			3	840	1/3
129								850	
144				10.8	6.40	450	7.2	880	1/3
151								740	
168				6.3				690	2

EXPERIMENTAL DATA (Cont.)
RUN 7-2

Time	COD_D	SUPERNATANT COD	SUPERNATANT NH_3	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
171									700	
190									680	
194	300	495		265	6.6	6.15	300	5.2		
216										1/3
240						5.30	115		600	
320	246	1135		410		4.72	57		370	
336					8.1				300	
368						4.5	42		220	
384						4.65				
385						7.09	686		190	
392							679		200	
432		700	32	345	6.6	5.6	130		220	
464						5/7.31	72/606		210	
512					9.2	5.97	175		250	
516	194	1097							210	
600							64/16			

EXPERIMENTAL DATA
RUN 7-3

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
0	15	9460	7460	2000	8860	7350	110	11,700
4								
9								
20								
25		8.80	6170	2010	6480	5370	800	8430
31								
45								
72		7300	5300	2000	5090	3930	1370	7630
76								
92								
100								
120	200	6830	4830	2000	4960	3770	1060	6880
129								
144								
151								
168								

EXPERIMENTAL DATA (Cont.)
RUN 7-3

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
171								
190								
194	295	6440	4500	1940	4350	3210	1290	6650
216								
240	274	6340	4430	1910	4350	3210	1220	6480
320	100	6310	4420	1890	3820	2700	1720	6050
332								
368	95							
384								
392								
432	86	5960	4100	1860	4160	3020	1080	5457
464	95							
512	101							
516	91	5370	3500	1870	3780	2690	810	4942
600								

EXPERIMENTAL DATA (Cont.)
RUN 7-3

Time	COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
0	141		310	306	6.95	600	1.0	990	
4								900	0
9				84	7.35		10.0		0
20				218	7.07		35.0	990	0
25	1275				7.00	1030		995	
31				108			20	995	0
45				92	7.12		30	995	0
72	1775			99	7.29		15	1000	0
76								995	
92				18				1000	0
100								1000	
120				18.9	7.6		40	1000	0
129								1000	
144				9.4	8.3	1590	30	990	
151								1000	
168					8.07			1000	

EXPERIMENTAL DATA (Cont.)
RUN 7-3

Time	COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
171								1000	
190								1000	
194				2.7	8.3	1580	10		0
216									
240					8.57	1421		1000	
320	1947			3.57	8.55	1330		1000	
332				20				1000	
368					8.50	1270		1000	
384								1000	
392						1230		1000	
432				23.2	8.3	1192		1000	
464					8.2	1254		1000	
512				66	8.31	1271		1000	
516	1267							1000	
600									

EXPERIMENTAL DATA
RUN 7-4

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
0	15	9200	7230	1970	8470	6960	270	12,100
4								
9								
20								
25		8580	6590	1990	7240	6160	430	9110
31								
45								
72		7360	5420	1940	5850	4780	640	7560
76								
92								
100								
120	300	6110	4220	1890	5000	3820	400	5860
129								
144								
151								
168								

EXPERIMENTAL DATA (Cont.)
RUN 7-4

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
171								
190								
194	329	5740	3830	1910	4780	3430	400	5400
216								
240	321	5820	3960	1860	5000	3700	260	5400
320	117	5780	3900	1880	4560	3290	610	5060
332								
368	106							
384								
392								
432	94	5580	3700	1880	4480	3280	420	5060
464	94							
512	92							
576	90	5480	3600	1880	4410	3150	450	5233
600								

EXPERIMENT DATA (Cont.)
RUN 7-4

Time	SUPERNATANT COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
0	150	173	295	204	6.95	600	21	750	
4								970	0
9				250	6.60		25		0
20				81	6.79		35	800	0
25	655	1950	665		7.00	660		750	
31				68				700	0
45				44	7.25		35	760	0
72	570			144	6.90		15	800	23
76								800	
92				44.5	7.40		25	700	9
100								670	
120		900	525	16.2			25	420	4
129								590	6
144				6.5	8.08	1630	20	670	1
151								600	0
168					8.30			995	0

EXPERIMENTAL DATA (Cont.)
RUN 7-4

Time	SUPERNATANT COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
171								800	
190								750	
194	370	770	595		8.5	1690	8		
216									0
240					8 6	1577		890	
320	405				8.7	1467		1000	
332								1000	
368				20	8.6	1368		1000	
384								1000	
392						1290		1000	
432					8.7	1259		1000	
464				1.9	8.7	1244		1000	
512				NMO	8.7	1212		1000	
576	345							1000	
600						1299			

EXPERIMENTAL DATA
RUN 7-5

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
0	15	10,400	8290	2110	9720	8160	130	13,700
4								
9								
20								
25		9530	7430	2100	8100	6850	580	10,700
31								
45								
72		8100	6000	2100	6640	5300	700	8600
76								
92								
100								
120	300	7330	5170	2160	6000	4300	870	7370
129								
144								
151								
168								

RUN 7-5 (Cont.)

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
171								
190								
194	418	6390	4220	2170	5220	3790	430	6360
216								
240	437	6360	4220	2140	5220	3790	430	5660
320	222	6150	4020	2130	4890	3340	550	5660
368	158							
384								
392								
432	141.8	6080	3960	2120	4750	3290	670	5109
464	145							
512	136							
576	132	5600	3530	2070	4650	3160	370	4845
600								

EXPERIMENTAL DATA (Cont.)
RUN 7-5

Time	SUPERNATANT COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
0	149	267	175	440	6.95	600	1.0	790	
4								800	0
9				368	6.60		1.0		0
20				88				900	0
25	500				7.10	800	42	900	
31				81				890	0
45				54	7.01		30	800	2
72	802			135	6.80		15	900	44
76									
92				41	7.30		30	990	16
100								990	
120		1520	775	18.9			30	780	3
129								500	1
144				10.5	7.95	1840	20	700	1
151								600	1
168					7.69			700	3

EXPERIMENTAL DATA (Cont.)
RUN 7-5

Time	SUPERNATANT COD_D	COD	VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZO
171								700	
190									
194	540	1064	415		7.9	2100	9	760	
216				0.23					
240					8.2	2070		750	0
320	302	1579	800		8.45	1886		700	
332								700	
368				17	8.5	1851		800	
384				11				680	
392						1742		750	
436					8.6	1710		800	
464					8.65	1680		800	
512				NMO	8.9	1575		1000	
576	380							1000	
600						1537			

EXPERIMENTAL DATA
RUN 7-6

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
0	15	9130	7190	1940	8300	6960	230	10,400
4								
9								
20								
25		8170	6200	1970	6300	5100	1100	9350
31								
45								
72		7280	5370	1910	5600	4300	1070	7780
76								
92								
100								
120		6874	4960	1914	5100	3880	1080	7030
129								
144								
151								
168								

EXPERIMENTAL DATA (Cont.)
RUN 7-6

Time	NH_3	TS	TVS	TFS	TSS	VSS	VS_D	COD
171								
190								
194		6070	4230	1840	4110	3050	1178	6070
216								
240		6000	4230	1770	3830	2785	1445	5518
320		5540	3790	1750	3290	2270		4960
332								
368								

EXPERIMENTAL DATA (Cont.)
Run 7-6

Time	COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
0	173	259	230	650	6.95	600	0.5	750	
4								985	0
9				50	7.19		0.4		0
20				317	7.52		1.0	990	0
25	1291				7.80	1030	1.0	995	
31				115				1000	0
45				100	7.85		2.5	1000	0
72	1970			47.6	8.20		4.0	1000	0
76									
92				48.2	8.30		5.0	1000	0
100								1000	0
120								1000	0
129								1000	0
144				42.6	8.70	1230	4.0	310	0
151		3950	2010					300	0

EXPERIMENTAL DATA (Cont.)
Run 7-6

Time	COD_D	SUPERNATANT COD	SUPERNATANT VSS	O_2 UPTAKE	pH	ALK	D.O.	SET	PROTOZOA
168					8.30			1000	0
171								1000	0
190									
194	1770				8.75	1250		1000	
216				10.5			4.0		
240					8.80	1160		1000	0
320	1818				8.80	1065		1000	
332								1000	
368					8.80	1009		1000	

APPENDIX J

EXPERIMENTAL RESULTS, RUN 8

REACTOR	EXPERIMENTAL CONDITIONS
8-1	Sludge heated to 50°C for 30 minutes prior to digestion
8-2	40°C, Control
8-3	40°C, 32 hr added 500 mg (25 mg/l) Choloramphenical
8-4	30°C, Control
8-5	30°C, Zero hours added 830 mg (42 mg/l) Choloramphenical 98 hour added 500 mg (25 mg/l)
8-6	30°C, added 500 mg (25 mg/l) Choloramphenical

Sludge picked up 2/20/73, 1230-1300 hours

Temperatures = 16°C

EXPERIMENTAL RESULTS, RUN 8-1

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	AIR/O_2 ml/min	pH	ALK	SET	PROTOZOA	D.O.
0	11800	8710	9800	7330	13200	1330	1500	7.1	797	0	0	4.4
3							800			998		4.8
6							900	7.05		1000	0	0.7
15							900	7.60		1000	0	4.5
24	10800	7790	9050	6820	1110	730	700	7.81	1650			3.7
31							800			999	0	
40							800	7.57		1000	2 (V)	1.5
41							100					
44												5.8
48	9490	6530	7900	5800	9250	790				1000		
56							200	7.58	2480	1000	2 (V)	6.6
65							200	7.85		1000		4.85
72												3.8
75							200				3(VC)	3.5
85												3.3

EXPERIMENTAL RESULTS, RUN 8-1 (CONT)

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	AIR/O_2 ml/min	pH	ALK	SET	PROTOZOA	D.O.
89							200	7.92		1000		
93											10 (C)	
96	8610	5640	7270	5030	7810		200	7.9	2780	1000	3 (C)	3.6
113							200	7.9		1000	8 (CM)	3.8
124							150	7.9		998		3.8
137							200	7.29		1000	15 (CM)	3.5
138												
144		5420			7340						14 (CM)	
162	8030	5090	6330	4360	6990	595	100	6.2	1150	998	0	6.0
173										990		
208										990		
276	7950	4980	6170	4150	6260	1222	70		1080	980		6.0

EXPERIMENTAL RESULTS, RUN 8-2

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	AIR/O_2 ml/min	pH	ALK	SET	PROTOZOA	D.O.
0	1130	8310	10300	8000	12500	315	1500	7.15	628	0	3	1.2
3							80			970		
6							100	6.86		990	0	9.5
15							40/400	7.08		950	0	0.1
24	10600	7610	9350	7020	10200	424	600	7.81	1710			2.1
31							700			970	1 (V)	3.5
40							650	8.1		998	(M)	3.6
42							100					
44												
48	9820	6810	8160	5930	9600	960	100			995		4.8
56							200	7.66	2050	1000	4 (M)	4.0
65							200	7.70		950		1.8
72							200				32	2.8
75							200	8.1				3.7
85												

EXPERIMENTAL RESULTS, RUN 8-2 (CONT)

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	AIR/O_2 ml/min	pH	ALK	SET	PROTOZOA	D.O.
89						315	1500	7.15	628	0	3	1.2
93											8	
96	8620	5680	7070	4920	7620		200	8.12	2750	970	7 (M/C)	3.8
113							200	8.1		980	1 (M)	4.1
124							150	8.21		980		4.8
137							150	8.29				6.5
138										950	1 (M)	
144											2 (M)	
162	8040	5170	6550	4370	6970	1440	100	8.4	3030	900		7.0
173										910		
208										990		7.5
276.5	7890	4900	6590	4270	6460	460	60	2970		998		7.5

EXPERIMENTAL RESULTS, RUN 8-3

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	AIR/O_2 ml/min	pH	ALK	SET	PROTOZOA	D.O.
0	11400	8460	10500	8020	12600		1500	7.12	632	0	9	0.2
3							80			980		
6							100	6.81		990	0	4.0
15							40/400	7.0		940	0	9.7
24	10600	7670	9360	7030	10300	424	700	7.81	1630			
31							400			980	0	3.2
40							300	7.7		998		
42							100					
44												5.5
48	9590	6830	8040	5880	9580	1100	100			998		
56							200	7.75	2200	1000	0	
65							100	7.9		970		3.9
72							100					4.4
75							100				1	4.2
85												

EXPERIMENTAL RESULTS, RUN 8-3 (CONT)

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	AIR/O_2 ml/min	pH	ALK	SET	PROTOZOA	D.O.
89							100	8.1		998		4.3
93												
96	9050	6160	7390	5200	8480		100	8.2	2480	990		4.4
113							100	8.12		990		4.5
124								8.07		1000		4.0
137							80	8.02		998	7	6.4
144											9	
162	8580	5720	6630	4570	8120	1189	80	8.2	2770	995		7.5
173										980		
208										995		
276.5	8680	5700	6670	4390	6920	1087	40		2680	998		7.5

EXPERIMENTAL RESULTS, RUN 8-4

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	pH	ALK	SET	PROTOZOA	D.O.
0	11300	8310	10600	8010	12000	968	7.15	623	0		1.0
3									999		0.8
6							7.30		1000	25	0.5
15							7.58		900	17	0.6
24	9890	6950	8830	6680	9760	242	7.25	1620			0.5
31									980	9	2.5
40									990	6	
44							7.41				2.4
48	9000	6130	7640	5620	8590	253			998		
56							7.19	1371	1000	1	2.5
65							6.51		998		4.0
72											
75										2	
85											
89							6.35		980		5.0

EXPERIMENTAL RESULTS, RUN 8-4 (CONT)

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	pH	ALK	SET	PROTOZOA	D.O.
93										0	
96	8730	5850	7120	5220	8000		6.31	852	1000	0	4.9
113							6.25		1000	1	5
124							6.29		998		6.4
137							6.30		990	1	6.3
144											
162	8430	5670	6510	4730	7240	266	6.30	731	800	1	6.3
173									850		
208									780		
276.5	8000	5120	5460	3920	5490	177		171	580		6.0

EXPERIMENTAL RESULTS, RUN 8-5

TIME,hr	TS	TVS	TSS	VSS	COD	COD_D	pH	ALK	SET	PTOROZOA	D.O.
0	11100	8150	10300	7840	11800	1040	7.25	635	0	14 (AV)	0.9
3									1000		
6							6.8		1000	7 (AV)	0.3
15							6.75		1000	9 (AV)	0.4
24	10700	7650	9470	7200	10900	379	7.5	1560			0.7
31									1000	4 (AV)	1.7
40									1000	4 (AV)	
44							7.85				1.8
48	9230	6430	8210	6080	9290	253			998		2.3
56							7.75	1720	1000	1 (VA)	2.0
65							7.20		998		2.7
72										2 (V)	4.0
75										2 (VA)	
85											
89							6.25		1000		4.8

EXPERIMENTAL RESULTS, RUN 8-5 (CONT)

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	pH	ALK	SET	PROTOZOA	D.O.
93											
96	8800	5960	7250	5390	8600		6.30	890	1000	0 (V)	4.9
113							6.3		1000	1 (V)	4.9
124							6.35		1000		6.0
137							6.49		1000	0 (R)	6.0
144											
162	8800	5910	7190	5250	8410	446	6.4	966	1000	2	6.2
173									1000		
208									1000		
276.5	8590	5700	6140	4310	7100	1703		733	950		6.0

EXPERIMENTAL RESULTS, RUN 8-6 (CONT)

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	pH	ALK	SET	PROTOZOA	D.O.
0	11500	8480	10800	8240	12800	203	7.10	655	0	14 (AV)	1.0
3									999		
6							7.50		1000	20 (AV)	0.4
15							6.91		998	20 (AV)	0.5
24	10400	7480	9380	7140	10700	227	7.28	1370			0.9
31									1000	12 (AVR)	1.8
40							7.6		998	10 (A)	2.8
44											2.7
48	9700	6740	8490	6260	9720	249			1000		
56							7.55	1740	1000	3 (V)	2.5
65							7.3		1000		2.1
72											2.5
75										4 (A)	
85											
89							6.25		1000	1	5.2

EXPERIMENTAL RESULTS, RUN 8-6 (CONT)

Time,hr	TS	TVS	TSS	VSS	COD	COD_D	pH	ALK	SET	PROTOZOA	D.O.
93										1 (V)	
96	8960	6070	7680	5680	8720		6.23	873	1000	0	5.2
113							6.4		1000	0	4.8
124							6.49		1000		6.0
137							6.45		1000	2	6.1
138											
144											
162	8790	5940	7040	5100	8020	454	6.30	882	995	3	6.0
173									980		
208									970		
276.5	8640	5620	6180	4360	6500	285	5.39	391	800		6.5

RESPIRATION RATES

Date/Time	T,hr	Σ T,hr	8-1	8-2	8-3	8-4	8-5	8-6
			mg/l/hr					
2/20 1630		0	21.6	180	180	123	103	133
2000	4	4	16.2	287	242	135	115	134
2330	3.5	7.5	261	151	111	119	225	114
2/21 0730	8	15.5	55	82	68	81	351	90
0900	1.5	17.0					204	
1330	4.5	21.5	32	64	52	68	81	74
2130	8	29.5	25	52	54	70	59	66
2/22 0830	11	40.5	85	38	49	50	48	40
1030	2	42.5	70					
1130	1	43.5	111					
1430	3	46.5	80	43	91	55	56	47
2330	9	55.5	34	80	60	48	67	46
2/23 1000	10.5	66	44	99	30	30	65	43
1530	5.5	71.5	32	75	27	15	34	43
1900	3.5	75.0	38	61	23			
2/24 0900	14	89	31	45	22	95	10	7.7
1630	7.5	96.5	27	35	19	8.8	9.0	5.4
2/25 0930	17	113.5	27	30	26	8.5	10	14
2000	10.5	124	28	18	20	6.5	8.1	11
2/26 0900	13	137	43	18	23	8.1	9.0	13
1600	7	144	49	20	18	8.1	7.7	13
2/27 0830	16.5	160.5	7.2	17	16	12	14	9.5
2200	13.5	174	3.6	14	14	9.4	8.6	13

RESPIRATION RATES

Date/Time	T,hr	Σ T,hr	8-1	8-2	8-3	8-4	8-5	8-6
			mg/l/hr					
3/1 2000	46	220	4.5	9.0	8.6	8.6	11	13
3/4			5.4	9.0	6.75	18.0	12.6	14.3
3/6 2200			4.0	8.55	10.0	8.55	16.6	18.4

APPENDIX K

EXPERIMENTAL DATA, RUN 9, MARCH 15, 1973

Digester 9-1

Time, hr.	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
0	31,900	28,600	23,300	37,400	6.75	1,460	1.5	1,000	3 (SV)
2					6.90		1.5	1,000	
9							8.5		
18	28,300	26,200	21,000	33,000	7.07	2,186	24	1,000	
24							11.2		33 (SV)
27							10.2		
31								1,000	
36									4
43	26,800	23,600	18,500	31,400			0.4		
48									
54					7.3		18	1,000	

Digester 9-1 (Cont.)

Time, hr.	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
64					6.85	3,425			
71	23.900	21,300	16,400	25,600				1,000	
72							8		
88					6.89		6.0		
111.5	23,700	20,100	15,600	25,100				1,000	
120							7.5	1,000	
125					6.40	1,741			
184	21,154	15,800	12,000	20,200					
264					6.49		4.0	1,000	3 (C)
269	19,900	15,700	11,600	18,300				1,000	
305	19,500	15,400	11,300	18,100	6.60	1,607		1,000	
317							6.0		
531	17,800	13,200	9,400	15,000	5.91	1,237		1,000	

EXPERIMENTAL DATA, RUN 9, MARCH 15, 1973

Digester 9-2

Time, hr.	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
0	9,820	9,100	7,380	11,100	6.9	607	24	1,000	1 (A/V)
6							15	1,000	
9									6 (A/V)
19					6.59		13.9	998	9 (A/V)
24	8,790	7,780	6,390	8,480			9.6		
27									8 (A/V)
31					6.59	1,036		990	
46									9 (A/V)
48									
54					6.79		15	998	
69.5	7,670	5,890	4,620	7,260	7.06	1,435	7.3	1,000	
79									2 (A/V)
98									

Digester 9-2 (Cont.)

Time, hr.	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
105					7.0		7.0	990	
115					6.42	640	9.0	998	
122.5	6,940	5,360	4,110	6,490				1,000	
126								1,000	
129									0
141					6.30		10.0	1,000	
150								990	
163	6,690	5,090	3,910	6,260					
168							10	910	
177					6.41	551		950	
212							6.4	850	
236	6,406	4,650	3,540	5,180				890	
238					6.38	512			

Digester 9-2 (Cont.)

Time, hr.	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
261								800	
312					6.18		6.2	750	1 (V)
319								750	
356	7,420	4,690	3,620	5,230	5.85	290		700	
367								700	
381									
584	6,450	3,900	2,710	4,330	6.51	261	6.2	490	

EXPERIMENTAL DATA, RUN 9, MARCH 15, 1973

Digester 9-3

Time, hr.	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
0	15,700	14,800	12,000	17,900	6.75	773	21	1,000	2 (V)
6							15.5	1,000	
9							15.0	1,000	3 (V)
19					6.70			1,000	6 (V)
24	13,300	12,100	9,660	12,800			13.8	1,000	
27								1,000	14 (V)
31					6.75	1,385		1,000	8 (V)
46								1,000	
48							11	1,000	
54					6.66			1,000	
69.5	12,000	10,500	8,170	12,000	7.00	1,901		1,000	
79							4.4	1,000	10 (V)
98							4.3	1,000	

Digester 9-3 (Cont.)

Time, hr.	TS mg/l	TSS mg/l	VSS mg/l	COD mg/l	pH	ALK mg/l	D.O. mg/l	SETTLING ml	PROTOZOA #OBS*
105					6.7		5.6	1,000	
115					6.22	856		1,000	
122.5	11,100	8,970	6,880	11,000			7.2	1,000	
126								1,000	
129								1,000	0
141					6.22			1,000	
150							9.0	1,000	
163	10,800	8,690	6,710	10,500				1,000	
168								1,000	
177					6.42	842		1,000	
212								1,000	
236	9,740	7,440	5,630	9,040			68	1,000	
238					6.32	735		1,000	
261								1,000	

Digester 9-3 (Cont.)

Time, hr.	TS mg/l	TSS mg/l	VSS mg/l	COD mg/l	pH	ALK mg/l	D.O. mg/l	SETTLING ml	PROTOZOA #OBS*
312							6.2	1,000	0
319								1,000	
356	11,302	7,760	5,860	8,750	6.31	739		950	
367									
381									
584	11,000	6,430	4,490	7,430	5.65	196	6.2	150	

EXPERIMENTAL DATA, RUN 9, MARCH 15, 1973

Digester 9-4

Time, hr. mg/1	TS mg/1	TSS mg/1	VSS mg/1	COD mg/1	pH	ALK mg/1	D.O. mg/1	SETTLING ml	PROTOZOA #OBS*
0	5,780	5,150	4,250	5,730	7.6	405	2.4	760	0 (V/A)
6							3.8	690	
9							4.3	550	0 (V)
19					7.7		3.9		1 (V/A)
24	4,890	4,200	3,460	4,410			4.8		
27									1 (V)
31					7.89	640		640	
46					7.70		4.8		
48									
54								780	
67					6.6		5.6		
69.5	4,330	3,320	2,730	3,910	6.50	302		790	
79									0

Digester 9-4 (Cont.)

Time, hr.	TS mg/l	TSS mg/l	VSS mg/l	COD mg/l	pH	ALK mg/l	D.O. mg/l	SETTLING ml	PROTOZOA #OBS*
98								980	
105					6.31		5.4	950	
115					6.3	275			
122.5	4,290	3,155	2,510	3,730				1,000	
126									
129								1,000	
141					6.20		2.0	900	
150							6.0	900	
163	4,200	3,030	2,470	3,570					
168								900	
177					6.29	265		830	
212								680	
236	4,352	2,760	2,220	2,423				600	
238					5.75	140			

Digester 9-4 (Cont.)

Time, hr.	TS mg/l	TSS mg/l	VSS mg/l	COD mg/l	pH	ALK mg/l	D.O. mg/l	SETTLING ml	PROTOZOA #OBS*
261								520	
312					5.4		6.0	300	1 (R)
319									
356	3,890	1,970	1,520	1,780	5.10	52		75	
367								75	
381									
584	3,680	1,540		2,290	4.5	35.3		50	

OXYGEN UPTAKE
mg/l/hr

Acration time, hr.	9-1	9-2	9-3	9-4
0	297	157.5	310.5	90
2	495	166.5	270	144
6	350	67.5	107.1	56.7
8		63.9	99.0	53.1
10	350	57.6	86.3	46.8
19	225	57.6	93.4	38.2
23	239	59.5	79.3	34.2
27	198	27.9	76.5	33.3
36		37.3	63.5	27.9
45	194	36.9	54.5	25.2
54	143	59.4	34.6	24.8
67	66.1	21.6	24.8	11.7
75		29.3	49.5	7.2
79	51.4	27.4	54.9	7.65
95	22.9	33.2	59.4	6.75
105		36.7	34.3	2.96
115	13.5	13		
141		4.85	0.54	0.81
150		0.4	11.7	0.9
167		2.7	13.8	2.34
172	16.2			
187	15.5			

OXYGEN UPTAKE (Cont.)

Acration time, hr.	9-1	9-2	9-3	9-4
220	15.5			
235		3.24	8.65	8.3
240		5.04	7.0	12.8
272		3.6	7.03	7.4
320	9.0	6.3	6.65	14.2
368	13.3	5.76	9.90	4.15
382	6.12	8.34	27.9	2.16

APPENDIX L

EXPERIMENTAL DATA RUN 10,

MARCH 22 to APRIL 29, 1973

RUN 10

OXYGEN UPTAKE

mg/1/hr

DATE/TIME	10-5 (30°)	10-6 (30°)	10-7 (27°)	10-8 (27°)	10-2 (42°)	10-4 (30°)
3-22/2300	15.8	8.84	30.1			
3-23/2030		13.5	24.8			
3-24/1930		20.5	46			
3-25/1930		20.7	58.6			
3-26/0815		29.2	46.4			
3-26/2030	18	24.8	46.0	13.5		
3-27/0740	15.6	29.5	56.0	16.0		
3-27/1650	17.1	37.1	43.1	17.5		
3-28/0820	18.0	22.7	36.6	17.3		
3-28/2100	17.3	25.2	40.2	20.2		
3-29/0630	19.8	31.3	48.5	19.7		
3-29/2010	22.5	27.2	48.5	22.6		
4-1/0900	16.2	41.0	54.0	18.5		
4-3/2000	5.85	43.0	40.5	47.2		
4-4/2000	5.85	27.9	---	20.5		
4-5/1930	6.40	24.8	55	36.0		
4-5/1300	10.5	44.6	43.2	27.7		
4-6/2030	7.39	33.3	40.5	28.6		
4-7/1045	7.93	25.4	38.5	24.9		
4-7/2115	9.73	25.2	52.1	24.5		
4-8/1945	11.40	36.4	56.5	28.8	97.2	

RUN 10 (Cont.)

DATE/TIME	10-5 (30°)	10-6 (30°)	10-7 (27°)	10-8 (27°)	10-2 (42°C)	10-4 (30°C)
4-9/2115	12.40	36.0	45.0	26.8	93.0	
4-10/0915	11.70	43.2	41.5	35	90.0	
4-10/2115	14.70	54.0	50.5	35	112	
4-11/0900	11.0	60.0	57.0	41.7	108	
4-11/2145	13.7	59.0	65.4	42.4	122	
4-12/1015	11.0	50.5	58.2	47.6	129	
4-12/2100	10.4	50.0	57.6	52.2	142	
4-13/2100	10.0	41.5	64.6	46.0	108	
4-14/2200	9.55	41	62.1	38.8	144	
4-15/0930					111	
4-15/2130	12.6	37.8	53.4	33.7	90	23
4-16/0930	12.0	41.4	52.6	33.8	124	34.4
4-17/0930	9.36	52.5	37.2	33.8	111	24.6
4-18/0900	9.72	39.5	37.2		123	12.6
4-20/0930	8.45	48.5	57.9	43	94.5	8.45
4-23/0915	14.5	50	96	41.9	148	15.8
4-23/0945			105			
4-23/1015			113.4			
4-23/2130			85			
6 min. after feed			140			
20 min. after feed			122			
4-24/0930	14.7	60	107	48.6	159	9.55
4-24/2145			90			

RUN 10 (Cont.)

DATE/TIME	10-5 (30°)	10-6 (30°)	10-7 (27°)	10-8 (27°)	10-2 (42°)	10-4 (30°)
4-25/0830	16.0	66.5	78.6	18	103.8	10.8
4-25/2300			87.4		140.4	
4-26/0930			21.8			
4-26/2045			48.6		121.5	
4-27/2145	17.6	52.2	70.2	63	174	13.9
4-28/0915			81	53	117	
4-29/0915			104		112	
4-29/2220			97.6	55	135	
4-5/4-26						
TOTAL	255.03	757	1399.8	770.1	1205	42.7
AVG	11.1	50	60.0	36.7	120.5	10.7

OXYGEN UTILIZATION

	10-2	10-4	10-5	10-6	10-7	10-8
VSS,IN mg/day	56,000	9,000	9,000	25,200	16,800	8,400
VSS,DES. mg/day	26,300	1,890	4,270	13,300	7,900	5,100
O_2 UPTAKE mg/l/hr	120	10.7	11.1	50	60	36.7
mgO_2/mgVSS	2.20	2.72	1.27	1.82	1.82	1.74

RUN 10

FEED SLUDGE

DATE	TS	TVS	TSS	VSS	COD
3-13	7490	5620	6810	5620	8870
3-27	9182	6784	8530	6800	
3-28			8385	6790	
3-29			9135	7355	
4-5			11670	9095	15206
4-6			10160	7995	12000
4-7			11055	8635	
4-8			10865	8525	
4-9			10865	8525	
4-9 evening			8490	6570	
4-10			11700	9145	
4-11			11155	8585	
4-12			12380	9610	
4-13					
4-14					
4-13/14			11660	9070	
4-14/15			8895	6815	
4-15/16			10230	7970	
4-18/19			9185	7220	
4-19/20			13675	9065	
4-24/25			11745	9440	15363

	NH_3	ORG. N	NO_3^-
4-11	23.3	845	45
4-14	27.4	818	50

DIGESTER 10-2

DATE	TSS	VSS	COD	ALK	pH
4-9	8205	5840			
4-11	6475	4410			
4-12	6270	4270	8008	2305	8.0
4-13	7390	5020			
4-15	6020	3895			
4-19	6210	3990			
4-20	6620	4485			
4-24	6980	4940			
4-25	7220	5115	8683	1484	7.5
4-26	8435	6050	10067	1607	7.1

DIGESTER 10-4

4-15	5745	3795			
4-19	5350	3425			
4-20	7150	3370			
4-24	5415	3680			
4-30	5135	3500	6107	612	6.15

DIGESTER 10-5

DATE	pH	ALK	TS	TVS	TSS	VSS	COD	NH_3	NO_3	ORG.N
3-28	4.9	60	5154	3292	3095	2420	3430	44	--	255
3-29					3100	2380				
3-30					3030	2240				
3-31					2860	2100				
4-6	5.4	80			1920	1410	3051			
4-7					2900	2155				
4-8					3065	2195				
4-9					3350	2365				
4-10					3170	2235				
4-11					3455	2450				
4-12	4.6	47			3515	2455	4492	1125	206	292
4-13					3620	2440		115	224	292
4-13 SUPER					480	415	711			
4-15					3990	2815				
4-19					3415	2475				
4-20					5510	3045				
4-24					4395	3135				
4-26	5.3	88			3445	2430	5344			

DIGESTER 10-6

DATE	pH	ALK	TS	TVS	TSS	VSS	COD
3-28	6.35	455	6044	4088	4495	3480	4640
3-29					4540	3500	
3-30					4650	3590	
3-31					4000	2990	
4-6	6.25	255			4520	3325	5807
4-7					4420	3370	
4-8					5650	4185	
4-9					5620	4210	
4-10					5400	4025	
4-11					4945	3595	
4-12	5.35	100			5195	3830	6934
4-13					5600	4125	
4-13 SUPER					220	220	570
4-15					5475	3990	
4-19					5340	3860	
4-20					5960	3420	
4-24					6325	4675	
4-26	5.01	86			7075	5255	9065

DIGESTER 10-7

DATE	pH	ALK	TS	TVS	TSS	VSS	COD	NH_3	ORG.N
3-28	6.30	339	6440	4088	4630	3550	4860	86	354
3-29					4720	3670			
3-30					4790	3610			
3-31					4650	3600			
4-6	7.21	566			5545	4005	6398		
4-7					5955	4290			
4-8					6495	4795			
4-9					6585	4855			
4-10					5710	4250			
4-11					3980	2945			
4-12	4.95	76			6070	4480	8106		
4-13					6260	4645			
4-13 SUPER					210	210	625		
4-15					5460	3965			
4-19					6010	4390			
4-20					8545	5195			
4-24					6980	5075			
4-25	4.62	88			6730	4930	9685		
4-26	7.6	627			7745	5505	8779		

DIGESTER 10-8

DATE	pH	ALK	TS	TVS	TSS	VSS	COD
3-28	6.47	382	6736	4642	5305	4135	6253
3-29					5110	4020	
3-30					5430	4220	
3-31					5070	3890	
4-6	5.5	125			3755	2760	4625
4-7					4155	3110	
4-8					4400	3310	
4-9					4765	3490	
4-10					4570	3330	
4-11					4665	3340	
4-12	5.65	131			4280	2970	5860
4-13					4775	3365	
4-13 SUPER					850	770	1117
4-15					4630	3225	
4-19					5165	3595	
4-20					6865	3910	
4-24					3950	2875	
4-26	8.2	906			5735	3805	6298

VSS ANALYSIS

FEED	10-2	10-4	10-5	10-6	10-7	10-8
9095			1410	3325	4005	2760
7995			2155	3370	4290	3110
8635			2195	4185	4795	3310
8525			2365	4210	4855	3490
8525			2235	4025	4250	3330
6570			2450	3595	2945	3340
9145			2455	3830	4480	2970
8585	3895		2440	4125	4645	3365
9610	3990	3795	2815	3990	3965	3225
9070	4485	3425	2475	3860	4390	3595
6815	4940	3370	3045	3420	5195	3910
7970	5115	3680	3135	4675	5075	2875
7220		3500	2430	5255	4930	3805
9065						
9440						
TOTAL 126,265	22,425	17,770	31,605	51,865	57,820	43,085
AVG 8418	4485	3554	2431	3990	4448	3314
%RED	47	58	71	53	47	61

SUPERNATANT QUALITY

		42° 3 day 10-2	30° 5 day 10-7	30° 6-2/3 day 10-6	30° 10 day 10-8	30° 15 day 10-5	40° + 30° 13 day 10-4
TSS	AB		210	220	850	480	
	A26		315	335	635	635	1065
VSS	A13		210	220	770	415	
	A26		290	335	600	565	825
COD	A13		625	570	1117	711	
	A26		550	603	710	1061	1420
NH_3	A13	368	76.8	87.8	123	113	
	A26	244	102	77	145	126	189
ORG.N	A13		41.2	38.4	80	49	
	A26		60		134	82	80
NO_3^-	A13	25	245	306	245	292	81
	A26	25					
NO_2	A26		56	25	71	92	162
	A29	160	92				

NITROGEN BALANCE

DATE		10-2	10-7	10-6	10-8	10-5	10-4
NH_3	(12)	362	91	77	126	113	
	(13)	368	88	93	132	115	
	(25)	274	77				
	(26)	244	113	77	162	129	184
ORG	(12)	428	381	445	294	206	
	(13)	434	434	365	296	224	
	(25)	458	403				
	(26)	557	521	450	417	274	327
NO_3^-	(12)	38	306	306	245	292	
	(13)	38	245	306	306	292	
	(25)	25	250				
	(26)	25	106	248	75	263	81
NO_2^-	(26)		56	25	71	92	162
	(29)	160	92				
TOTAL							
	(12)	988	870	853	736	703	
	(13)	999	858	789	805	723	
	(25)	917	822				
	(26)	986	741	800	725	758	754

		NH_3	ORG	NO_3	NO_2	TOTAL	
FEED	(13)	23	845	45	25	914	
	(14)	27	818	50		868	
	(25)			63			

SETTLING DATA, ml

	10-7	10-6	10-8	10-5
AVG 4-13, 4-18 and 4-23	313	310	157	213

APPENDIX M

EXPERIMENTAL DATA RUN 11

MAY 1 TO JUNE 12, 1973

Six 20 liter reactors fed in series each with a 2.5 day detention time (numbers 1, 2, 3, 4, 5 and 6) and two 10 liter reactors with five and ten day detention times respectively (numbers 7 and 8).

FEED SLUDGE

DATE	TSS	VSS	COD	TVS
5/18	12,165	7,160		
5/21	8,965	5,945		
5/22	12,620	8,055		
5/24	11,200	7,270		
5/25	7,940	5,165		
5/27	19,255	9,950		
5/29	15,880	10,775		
5/30	12,210	8,090		
5/31	11,515	7,905		
6/1	14,470	10,020		
6/2	14,105	9,800	15,500	10,076
6/5	11,345	7,985		
6/6	11,625	8,230		
6/7	11,770	8,350		
6/10	9,795	7,270		
6/12	11,315	8,525		

DIGESTER VSS

DATE	#1	#2	#3	#4	#5	#6	#7	#8
5/18	8260	5610	4640	4020	2575	2745	6255	5840
5/21	6010	5290	4485	3735	3490	2940	5630	5405
5/22	5700	5330	4550	4115	3435	3125	5460	5865
5/24	5150	--	4255	--	3135	--	4975	5255
5/25	5425	4675	4780	4070	3435	3135	5375	5050
5/28	6675	4760	4620	4580	3945	3485	5735	5270
5/30	6035	4845	4070	4200	3930	3745	5380	4725
6/1	5700	5200	4410	4125	3825	3795	5420	4760
6/2	5805	5335	4575	--	3500	3615	4855	4290
6/12	5845	4755	4050	4075	3895	3090	4225	3825

DIGESTER TVS

6/12	6766	5560	4856	4846	5104	4356	5752	5550

DIGESTER COD

6/12	9568	7155	7413	6896	9999	6293	--	6034

DIGESTER NITROGEN

FORM	#1	#2	#3	#4	#5	#6	#7	#8
NH_3-N	18	72	89	95	89	86	78	101
ORG-N	620	489	390	361	315	306	462	343
NO_2^--N	132	154	164	154	180	162	62	66
NO_3^--N	132	212	219	250	250	270	238	275

FEED

NH_3-N	34
ORG-N	926
NO_2^--N	15

MAY 25, 1973

NH_3^--N	42	60	69	75	84	89	110	105
ORG-N	540	385	417	346	283	245	537	432
NO_2^--N	64	81	108	120	125	137	43	52
NO_3^--N	165	390	390	390	390	390	390	410

FEED

NH_3-N	23
ORG-N	845
NO_3^--N	45
NO_2^--N	25

JUNE 12,1973

FORM	#1	#2	#3	#4	#5	#6	#7	#8
NH_3-N	36	63	95	30	63	89	--	--
ORG-N	625	440	397	376	337	290	--	--
NO_2^--N	95	151	103	108	117	115	--	--
NO_3^--N	210	270	87	219	262	260	--	310

FEED

NH_3-N	30
ORG-N	920
NO_2^--N	20
NO_3^--N	0

RESPIRATION RATES

DATE	#1	#2	#3	#4	#5	#6	#7	#8
5/18	124	55	20	11	8	4	89	58
5/21	88	38	17	12	9	5	117	54
5/22	100	46	20	12	5	5	68	27
5/23	86	38	18	11	5	4	65	30
5/24	86	35	17	8	5	4	55	33
5/25	68	32	13	7	5	2	42	36
5/28	50	18	9	8	4	2	43	30
5/30	71	31	12	7	5	2	57	42
6/1	68	34	16	7	2	2	60	33

SUPERNATANT DATA

VSS

DATE	#1	#2	#3	#4	#5	#6	#7	#8
5/25	260	520	670	560	770	770	300	140

COD

5/25	520	740	1000	1960	1000	2200	240	370

SETTLING DATA, ml

5/25	500	380	340	260	180	150	280	250
6/12	500	350	300	280	280	220	--	--

AFTER DENITRIFICATION IN #3

6/12	500	400	880	400	350	180	--	--

STABILITY RESULTS, days

5/25	3	5	8	10	30	50		

pH AFTER DENITRIFICATION

6/12	4.5	4.3	6.8	4.4	4.3	4.4		

APPENDIX N

Digester Heating Costs

Heat Loss From Digester:

2,600 Btu/hr/1000 ft^3 (MOP #8, ASCE, 1967), Correction factor for middle states = 0.5. Thus, 1300 Btu/hr/1000 ft^3 or for 1 MGD plant

= 405,000 Btu/day

To Raise Sludge Temperature:

$Q = WC\ (T_2 - T_1)$

T_1 = Activated Sludge Temp, 54°F
T_2 = Digester Temperature, 86°F

For 1 MGD plant
Q = (7750 gal/day)(8.34 lbs/gal)(1)(32)

= 2,060,000 Btu/day

Total Btu for 1 MGD Plant:

= 2,465,000 Btu/day

For 20 MGD Plant:

= 49,300,000 Btu/day

or

= 2,054,166 Btu/day

Say #2 Fuel Oil

or 100,000 Btu/gal at 70% eff.

Thus, 20 gal/hr at $.35/gal

or $168/day

= $61,320/yr

Operation Costs:

Fuel	$61,000
Maintenance	5,000
Dep.	5,000
Int.	4,000
	$75,000/yr

Solids:

(7750 gal/day)(8.34)(9000)(20 MGD)

= 11,634 lbs/day
= 5.82 T/day

Thus, Costs To Heat:

= $35/Ton for 9000 mg/l feed

or

= $17,50/Ton for 2% feed

Plant Capacity: 1 MGD

Population: 10,000

Waste Sludge Flow: .85% of plant flow or 7,750 gal/day

Solids Conc. of was: 9000 mg/l

Detention Time: 12.5 days

Digester Vol: 12,800 ft^3

Air Flow: 20 cfmper 1000 ft^3

Oxygen Required: 1.8 g/gVss destroyed

Solids: 580 lbs/day

Thesis 151981
R3296 Rein
c.1
Improved aerobic digestion through temperature and solids control.